Diamond Detectors

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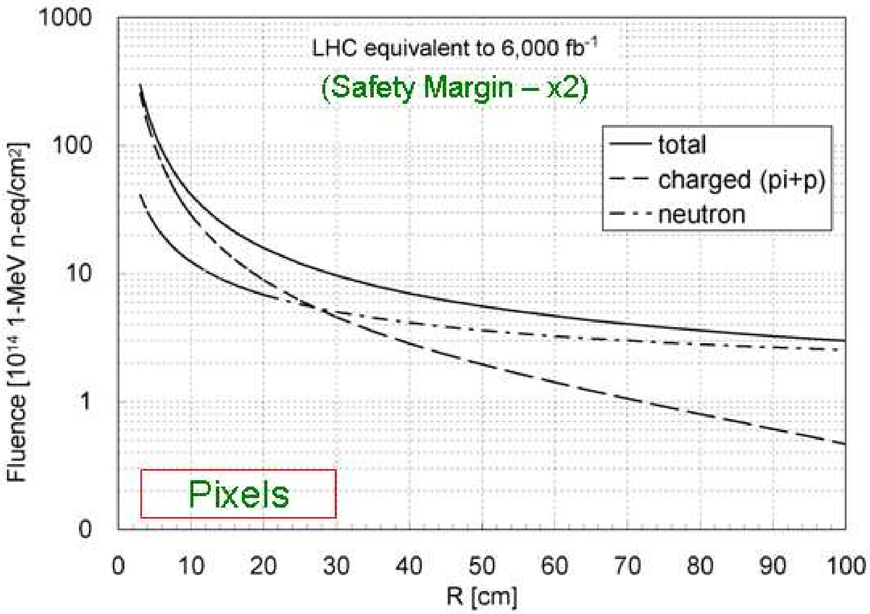
Outline of the Talk

- **Introduction - Motivation**
- **General Properties and Synthesis**
- **Charge Collection and Other Properties**
- **Radiation Hardness**
- **Applications - Beam Monitoring, Diamond Pixel Trackers**
- **Future Applications - ATLAS DBM, CMS PLT**
- **Summary**

Physics Experiments at the Energy Frontier

Use facilities with particles with high energy (probe small distances) and high intensity/luminosity (new physics reach). Need electronic grade detectors.



HEP experiments are physically large devices composed of high precision inner detectors (r=3-25cm) which must withstand large radiation doses!

Radiation Tolerance Scale of inner layers is $\sim 10^{16}$ *cm*$^{-2}$ *or* $\sim$ *500Mrad*

Motivation: Particle Detection Close to Interaction Region of Experiments

Tracking Devices at the High Energy Facilities (LHC/similar environments):

→ Inner layers closest to what is going on in an interaction

→ Inner detector layers must provide high precision (to tag b, t, Higgs, ...)

→ Inner detector layers must survive! → what does one do?

Look for a Material with Certain Properties:

- Radiation hardness (no frequent replacements)
- Low dielectric constant → low capacitance
- Low leakage current → low readout noise
- Good insulating properties → large active area
- Room temperature operation, Fast signal collection time → no cooling

Material Presented Here:

- Polycrystalline Chemical Vapor Deposition (pCVD) Diamond
- Single Crystal Chemical Vapor Deposition (scCVD) Diamond

- *Reference* → http://rd42.web.cern.ch/RD42

Introduction: The RD42 Collaboration

K. Andeen[17], M. Artuso[24], F. Bachmair[28], L. Bäni[28], M. Barbero[1], V. Bellini[2], V. Belyaev[15], E. Berdermann[8], P. Bergonzo[14], S. Blusk[24], A. Borgia[24], J-M. Brom[10], M. Bruzzi[5], G. Chiodini[31], D. Chren[22], V. Cindro[12], G. Claus[10], M. Cristinziani[1], S. Costa[2], J. Cumalat[23], A. Dabrowski[3], R. D'Alessandro[6], W. de Boer[13], M. Dinardo[23], D. Dobos[3], W. Dulinski[10], V. Eremin[9], R. Eusebi[29], H. Frais-Kölbl[4], A. Furgeri[13], C. Gallrapp[3], K.K. Gan[16], J. Garofoli[24], M. Goffe[10], J. Goldstein[20], A. Golubev[11], A. Gorišek[12], E. Grigoriev[11], J. Grosse-Knetter[27], M. Guthoff[13], D. Hits[28], M. Hoeferkamp[25], F. Hügging[1], H. Jansen[3], J. Janssen[1], H. Kagan[16,◇], R. Kass[16], G. Kramberger[12], S. Kuleshov[11], S. Kwan[7], S. Lagomarsino[6], A. La Rosa[3], A. Lo Giudice[18], I. Mandic[12], C. Manfredotti[18], C. Manfredotti[18], A. Martemyanov[11], H. Merritt[16], M. Mikuž[12], M. Mishina[7], M. Mönch[28], J. Moss[16], R. Mountain[24], S. Mueller[13], G. Oakham[21], A. Oh[26], P. Olivero[18], G. Parrini[6], H. Pernegger[3], R. Perrino[31], M. Pomorski[14], R. Potenza[2], A. Quadt[27], K. Randrianarivony[21], A. Robichaud[21], S. Roe[3], S. Schnetzer[17], T. Schreiner[4], S. Sciortino[6], S. Seidel[25], S. Smith[16], B. Sopko[22], S. Spagnolo[31], S. Spanier[30], K. Stenson[23], R. Stone[17], C. Sutera[2], M. Traeger[8], W. Trischuk[19], D. Tromson[14], J-W. Tsung[1], C. Tuve[2], P. Urquijo[24], J. Velthuis[20], E. Vittone[18], S. Wagner[23], R. Wallny[28], J.C. Wang[24], R. Wang[25], P. Weilhammer[3,◇], J. Weingarten[27], N. Wermes[1]

◇ Spokespersons

102 Scientists

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31 Institutes

General Properties and Synthesis

- chemical vapor deposition
- phase diagram

Comparison of Various Materials

Property	Diamond	4H-SiC	Si
Band Gap [eV]	5.5	3.3	1.12
Breakdown field [V/cm]	10^7	4×10^6	3×10^5
Resistivity [Ω-cm]	$> 10^{11}$	10^{11}	2.3×10^5
Intrinsic Carrier Density [cm^{-3}]	$< 10^3$		1.5×10^{10}
Electron Mobility [$cm^2V^{-1}s^{-1}$]	1800	800	1350
Hole Mobility [$cm^2V^{-1}s^{-1}$]	1200	115	480
Saturation Velocity [km/s]	220	200	82
Mass Density [g cm^{-3}]	3.52	3.21	2.33
Number Density [$\times10^{22}$ cm^{-3}]	17.7	8.4	5.0
Atomic Charge	6	14/6	14
Dielectric Constant	5.7	9.7	11.9
Displacement Energy [eV/atom]	43	25	13-20
Energy to create e-h pair [eV]	13	8.4	3.6
Radiation Length [cm]	12.2	8.7	9.4
Spec. Ionization Loss [MeV/cm]	4.69	4.28	3.21
Ave. Signal Created/100 μm [e]	3600	5100	8900
Ave. Signal Created/0.1% X_0 [e]	4400	4400	8400

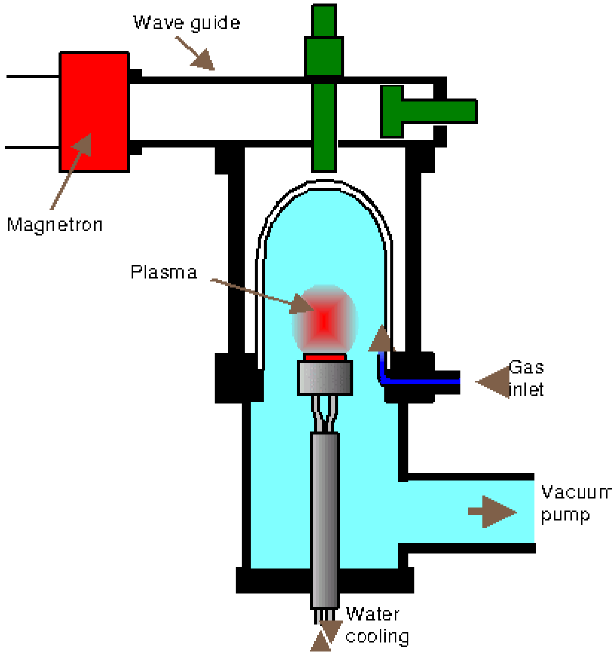
Low dielectric constant - low capacitance   Large bandgap - low leakage current

Low cross-section - radiation hard   Large energy to create an *eh* pair - small signal

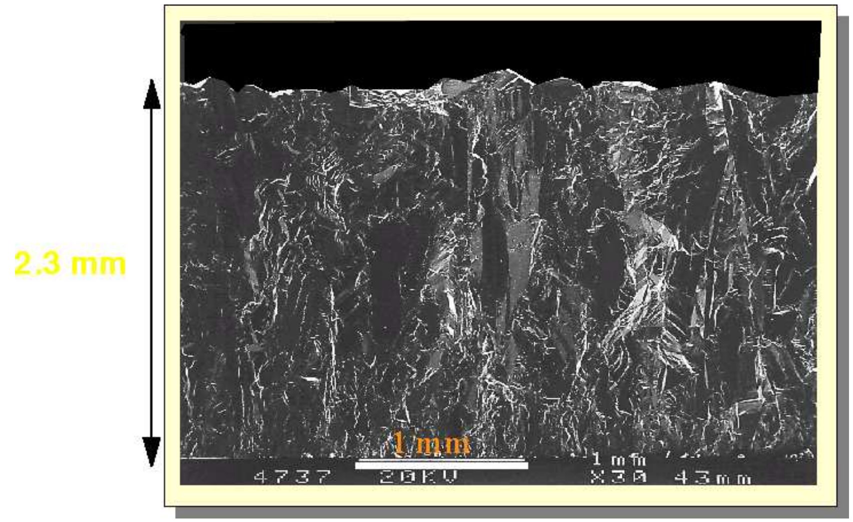
General Properties and Synthesis

Chemical Vapor Deposition (CVD) Diamond Growth

Micro-Wave Reactor Schematic



Side View of pCVD Diamond

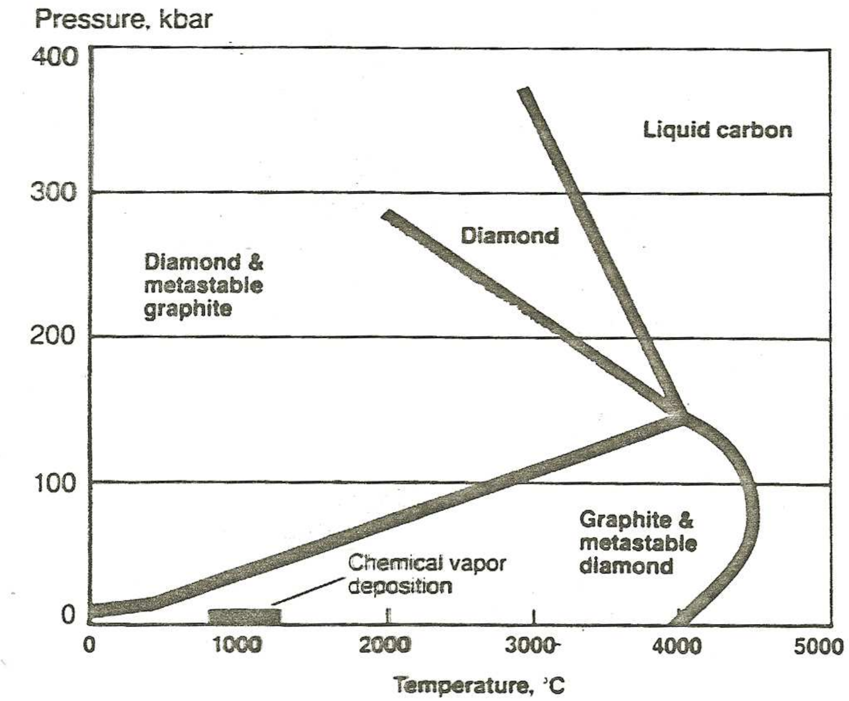


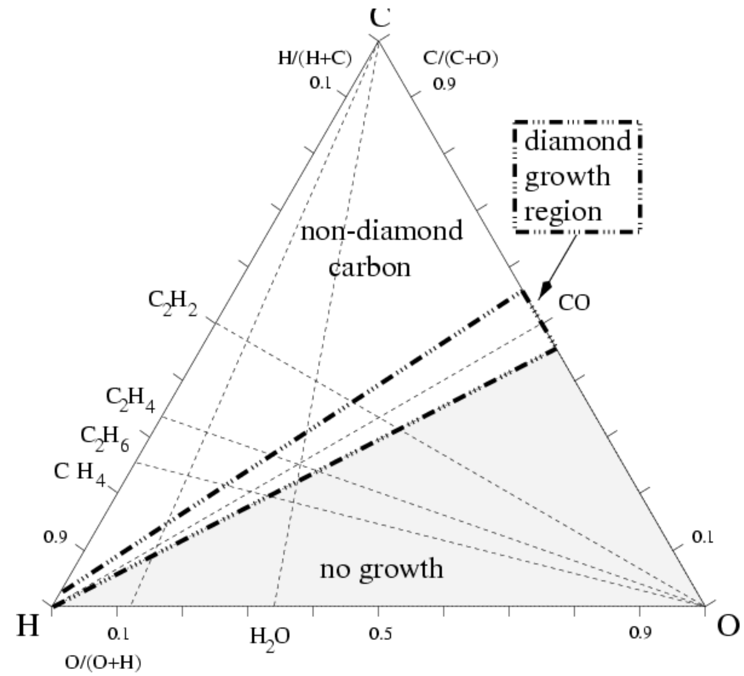
(Courtesy of Element Six)

- Diamonds are “synthesized” from a plasma
- The diamond “copies” the substrate

Large binding energy - radiation hard Low dielectric constant (5.7) - low capacitance
Large bandgap (5.5eV) - low leakage current Large energy to create *eh* pair - small signal

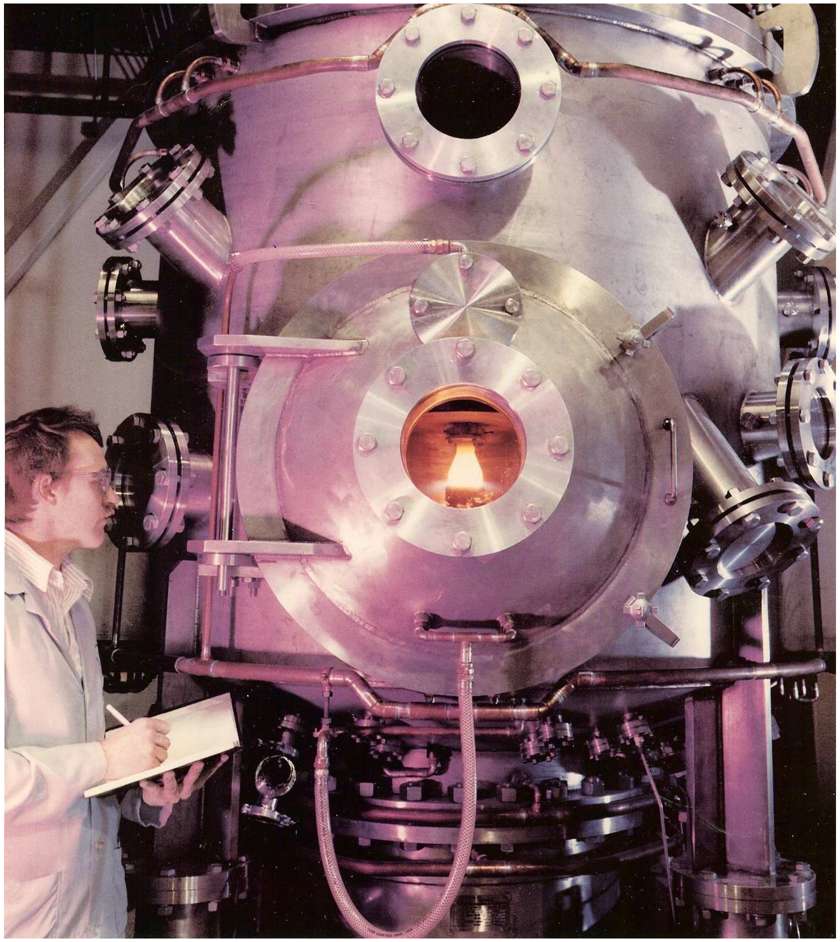
Phase Diagrams

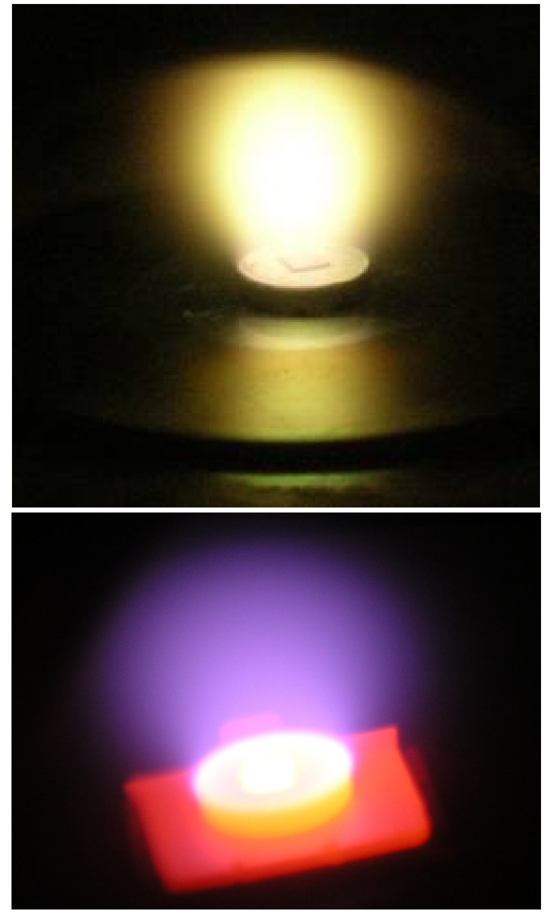




- Natural diamond grown at high pressure and high temperature.
- CVD diamond grown at low pressure and mid temperature!
- CVD process needs correct combination of C, H, O to grow electronic grade diamond.
- CVD process needs time to remove graphite $\rightarrow$ slower is better!

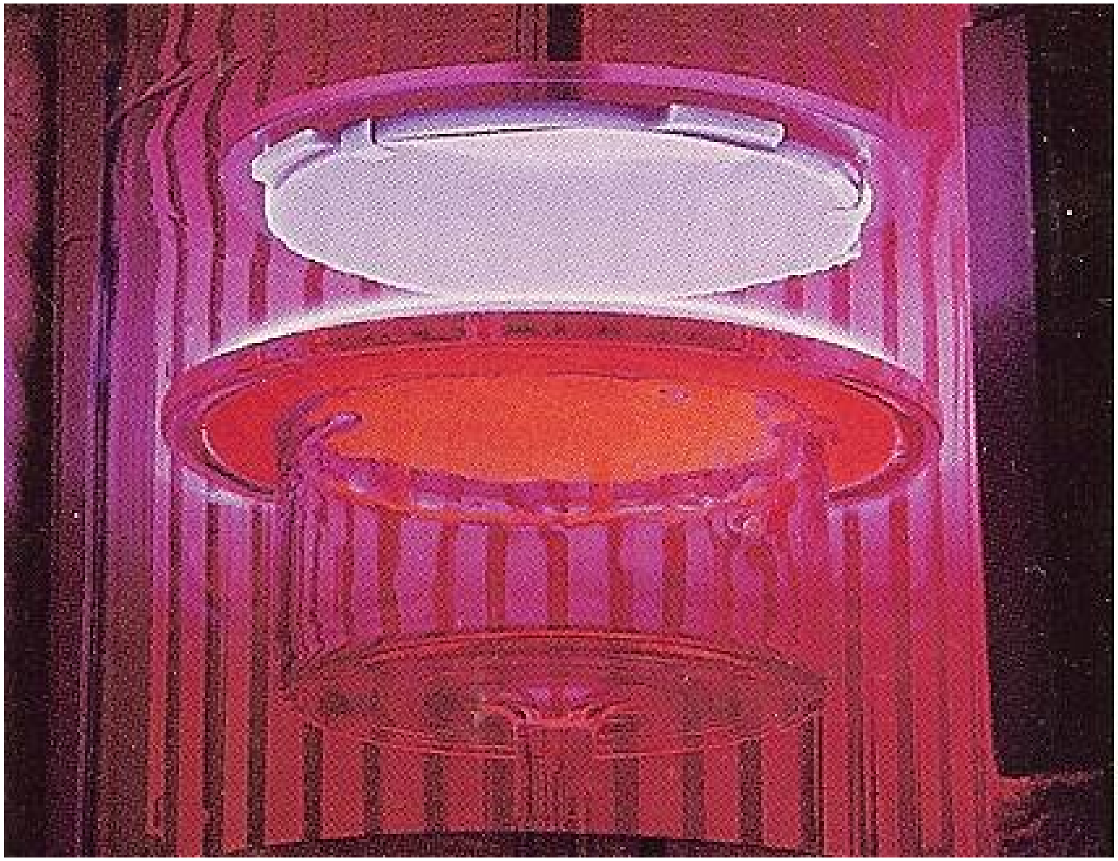
CVD Synthesis





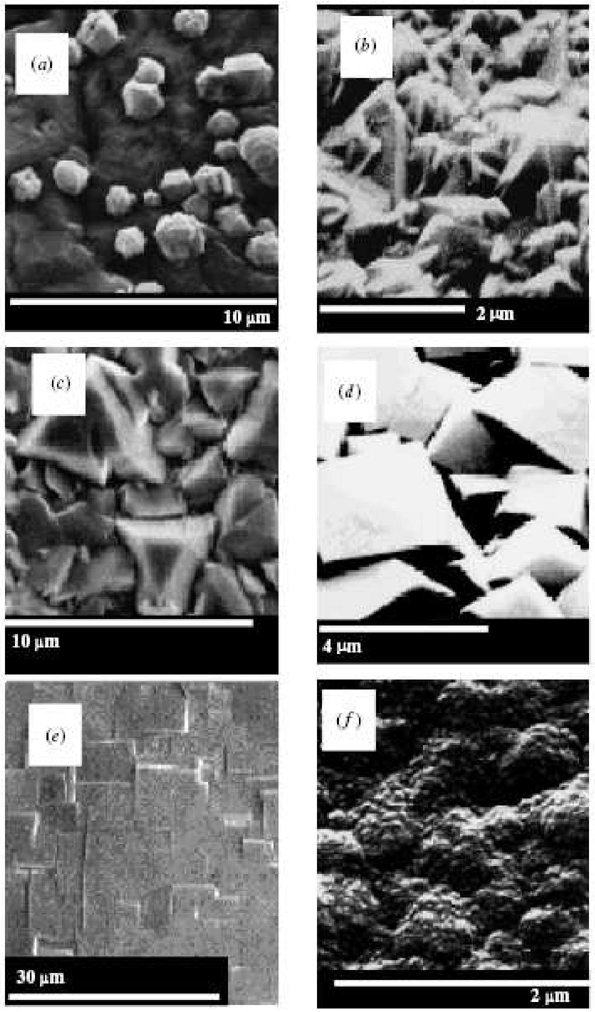
- Pictures of the different diamond growth plasmas.

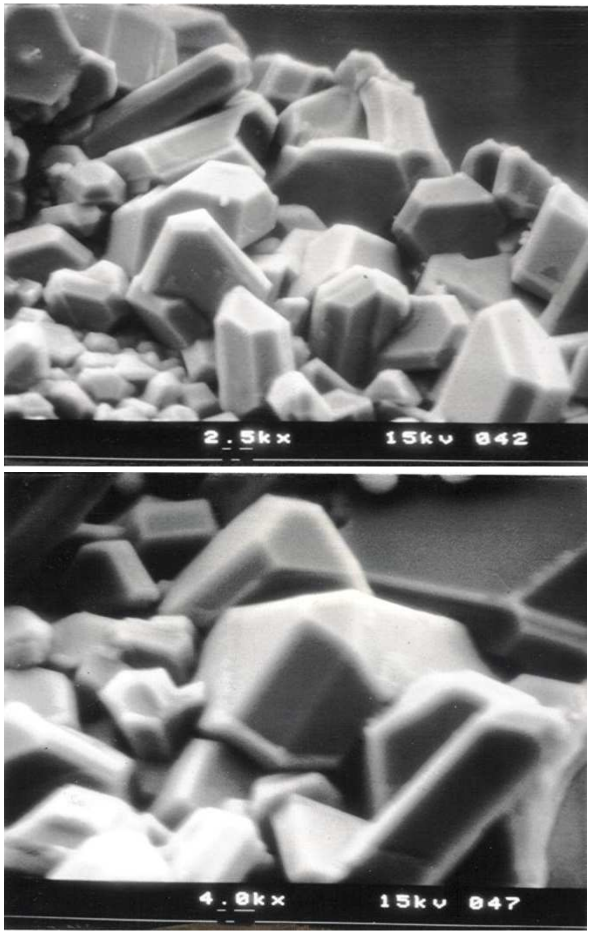
CVD Synthesis



- Chemical Vapor Deposition is a low pressure, mid temperature process.

CVD Diamond SEM

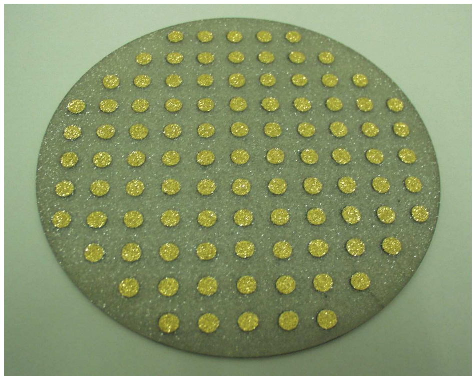
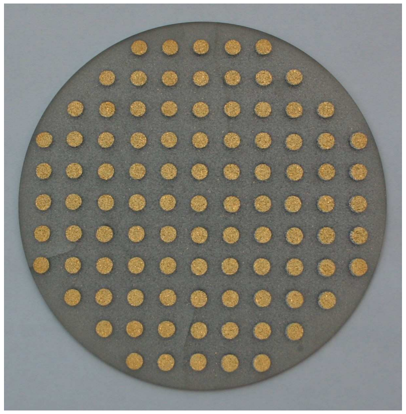


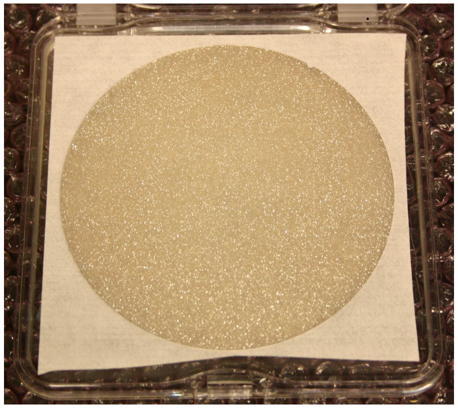


- SEM pictures of the different diamond growth surfaces.
- Right pictures grown with an oxyacetylene torch.

General Properties and Synthesis - Recent CVD Diamond Material

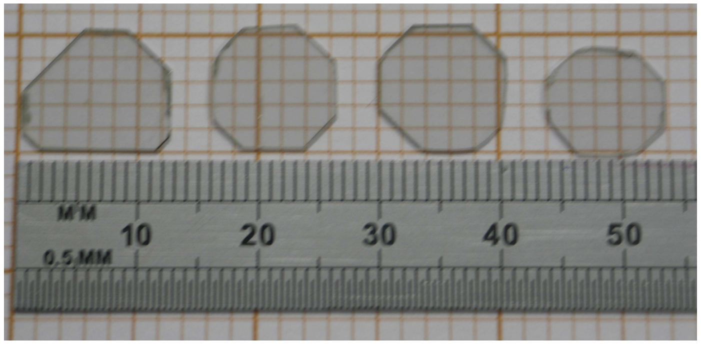
Recent Polycrystalline CVD Diamond



- New wafers (12 cm diameter) continually being produced.
- Wafer collection distance now typically 250μm to 320μm.

Recent Single Crystal CVD (scCVD) Diamond



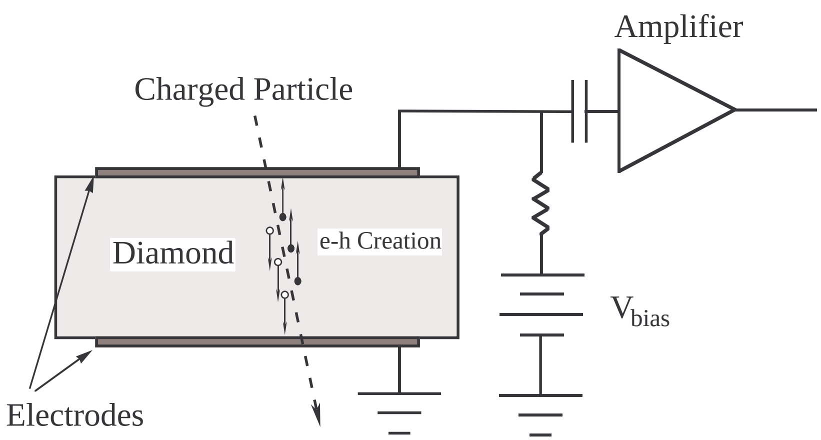
scCVD diamond has been grown $\approx$ 5-10 mm $\times$ 5-10mm, $>$1 mm thickness.

Charge Collection and Other Properties

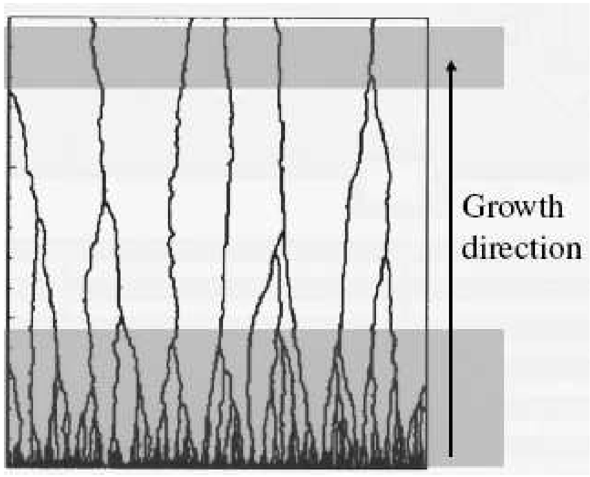
- collection distance
- polycrystalline, single crystal
- erratic dark currents

Detectors Constructed with Diamond:

Signal formation



pCVD Schematic Side View



- d=$(\mu_e\tau_e + \mu_h\tau_h)$E   where d = collection distance = ave. dist. e-h pair move apart
- d=μEτ = vτ

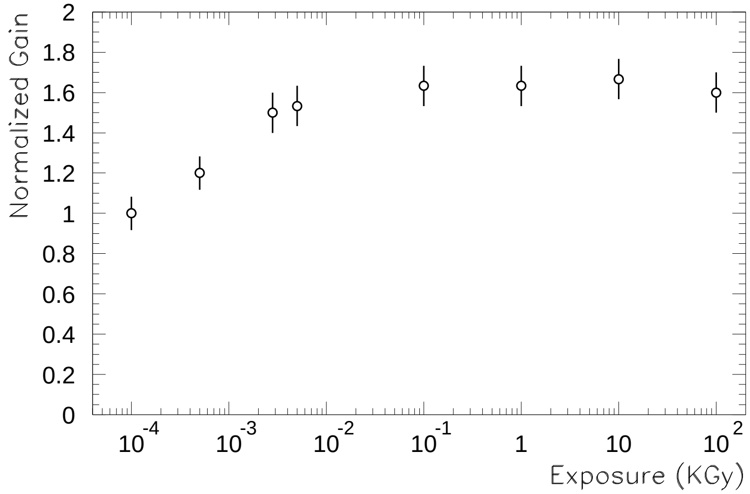
  with $\mu = \mu_e + \mu_h \rightarrow$ v = μ E

  and $\tau = \frac{\mu_e\tau_e+\mu_h\tau_h}{\mu_e+\mu_h}$
- Q=$\frac{d}{t}$Q$_0$ $\rightarrow$ for large charge need good collection distance - must maximize μ and τ
- I=Q$_0\frac{v}{d}$

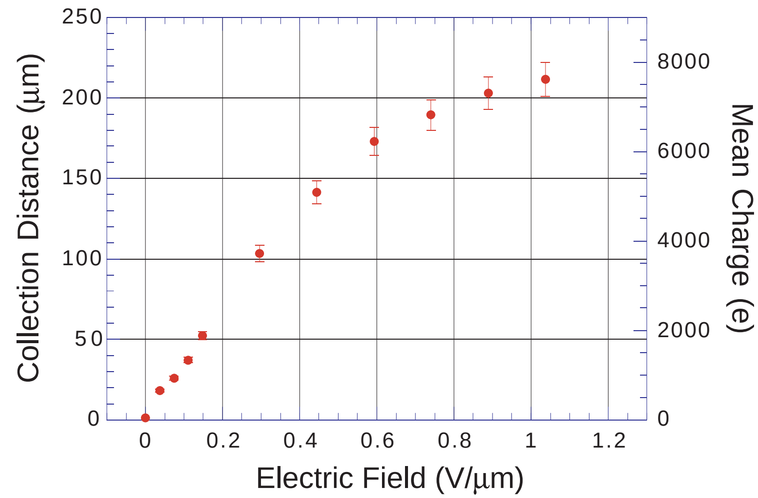
Charge Collection - pCVD Pumping

Characterization of Diamond:

Signal formation



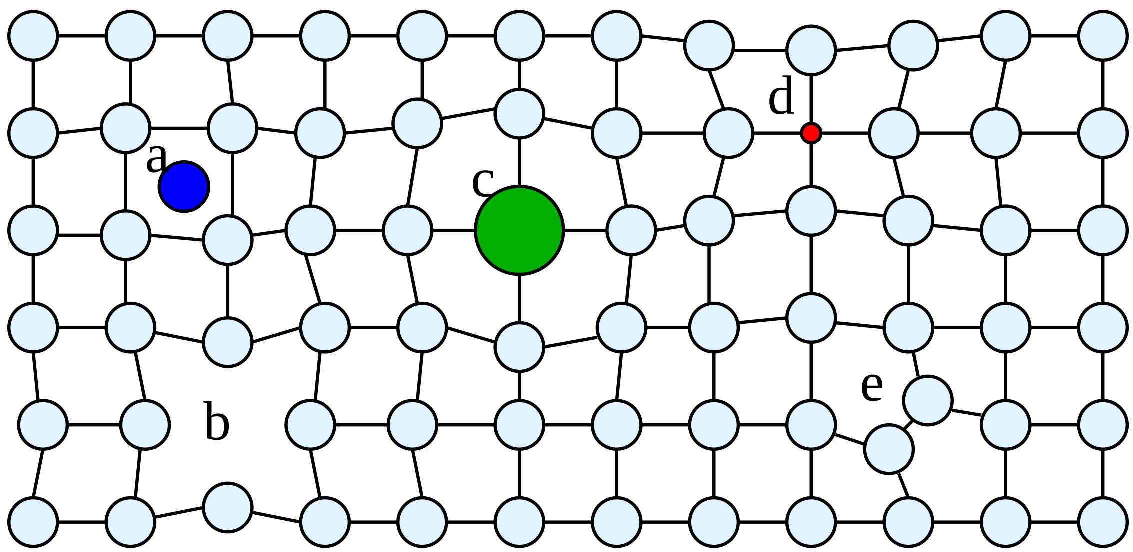
Signal versus applied electric field



- High quality pCVD diamond typically "pumps" by a factor of 1.5-1.8
- Traps/defects in material → ionization creates carriers which may fill traps
- Can de-pump (empty traps) at high temperature (300-400C)
- Usually operate at 1V/μm → drift velocity saturated
- Collection Distance of 100μm → Average Charge of 3600e
- Test Procedure: dot → strip → pixel

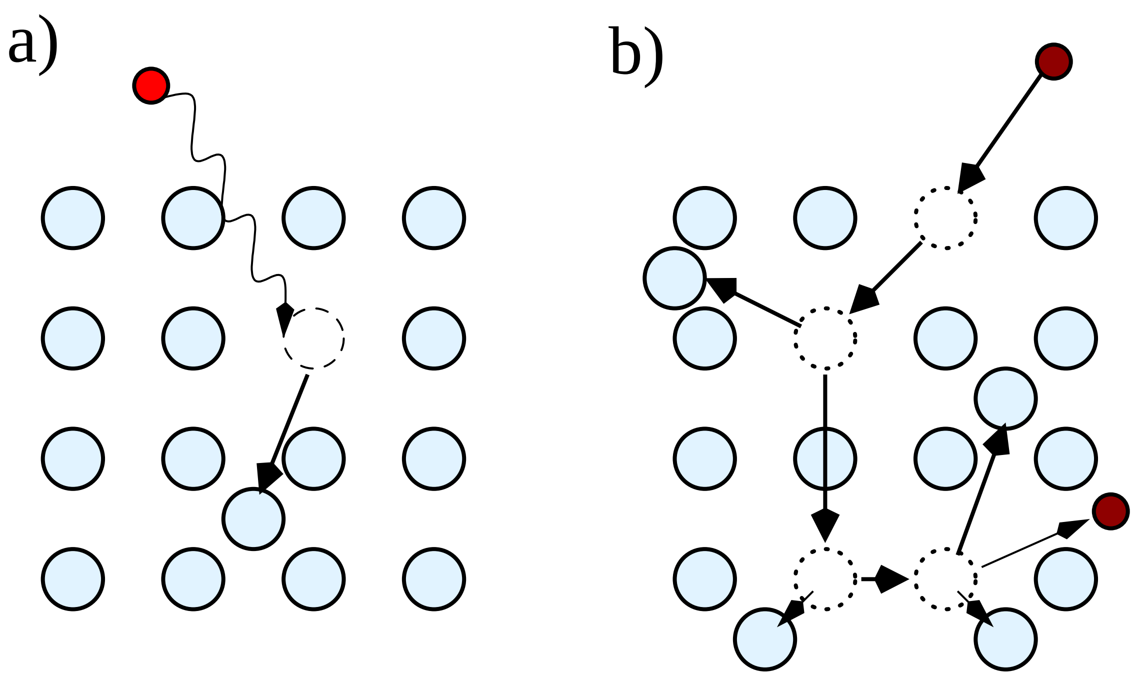
Defects in Diamond

- Properties of diamond (electrical conductivity, thermal conductivity, carrier mobilities and radiation hardness) depend on the concentration of defects.
- Point defects: interstials and vacancies.
  - a-foreign interstitial (e.g. H, Li)
  - b-vacancy
  - c,d-foreign substitutional (e.g. N,P,B)
  - e-self interstitial



Radiation Induced Defects in Diamond:

- Radiation also causes defects
  - a) e, γ knocks an atom from its lattice site and creates a vacancy interstitial pair
  - b) hadron knocks an atom from its lattice site with the creation of a cascade of secondary knock-on atoms



Effects of Defects in Diamond:

Defects are characterised by their position in the band gap and their cross section to capture a charge. The energy of the trap (E_t), temperature (T) and the Fermi level (E_f) determine the occupation of the state (F)

$$F(E_t) = \frac{1}{1 + e^{\frac{E_t - E_f}{kT}}}$$

Trap levels with $(E_t - E_f)$ of a few eV (deep traps) are therefore practically not occupied at room temperature ($kT << (E_t - E_f)$ but can be filled by the excess carriers generated by ionization.

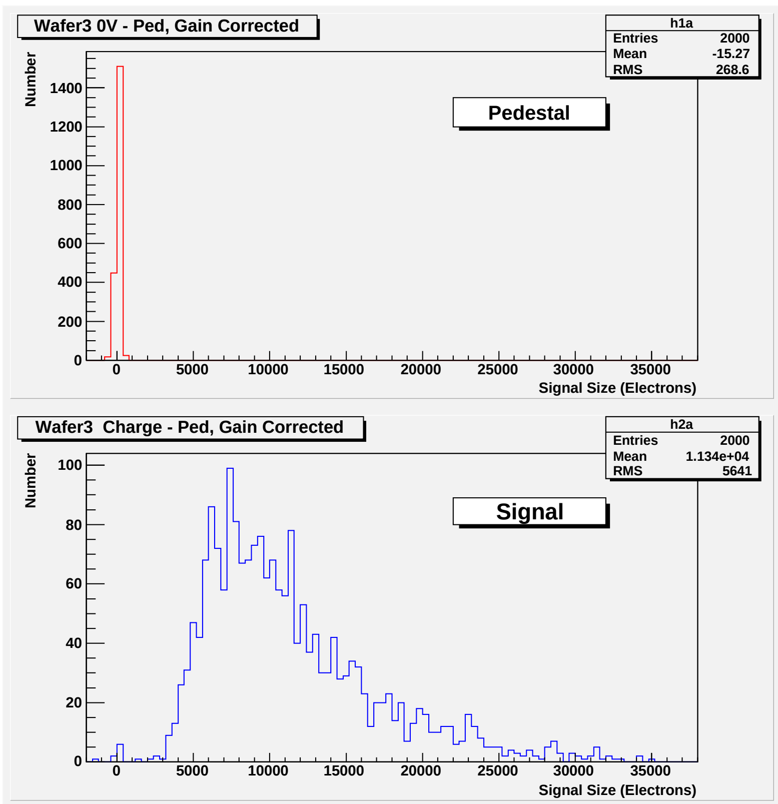
Boron produces $E_\Delta = 0.37$ eV
Nitrogen produces $E_\Delta = 1.86$ eV

"I also brought it [the diamond] to some kind of glimmering light by taking it into bed with me, and holding it a good while upon a warm part of my naked body" Sir Robert Boyle, reported Oct 28, 1663 to the Royal Society of London.

Charge Collection - Polycrystalline CVD Diamond

pCVD Material: pCVD Diamond Measured with a ^{90}Sr Source

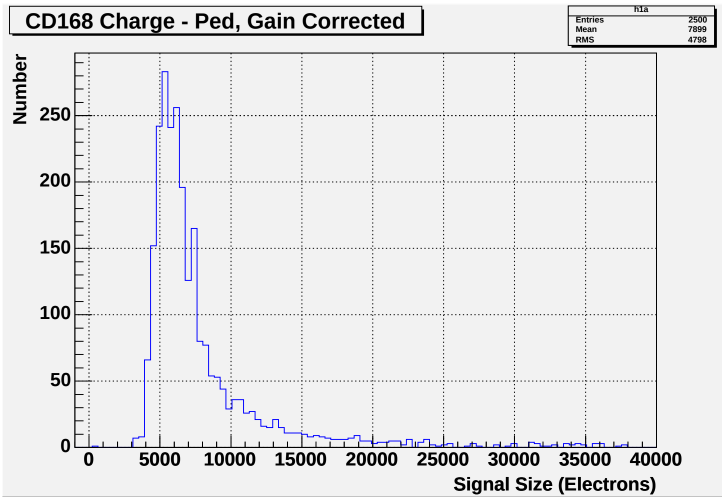
- Contacts on both sides - structures from μm to cm
- Usually operate at E=1-2V/μm
- Test Procedure: dot $\rightarrow$ strip $\rightarrow$ pixel on same diamond!

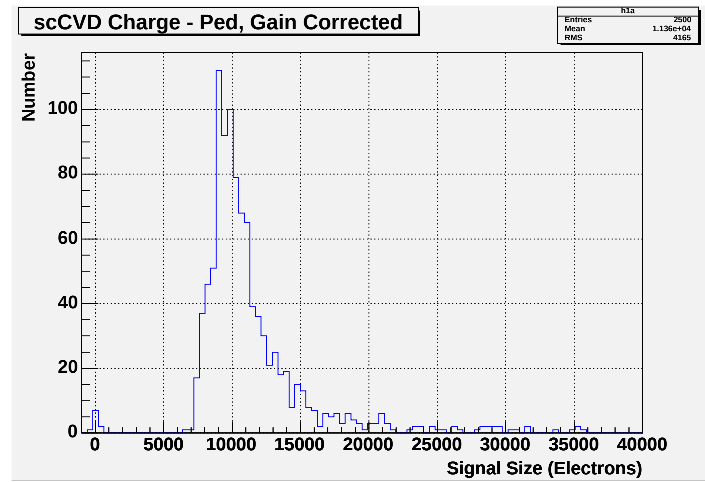


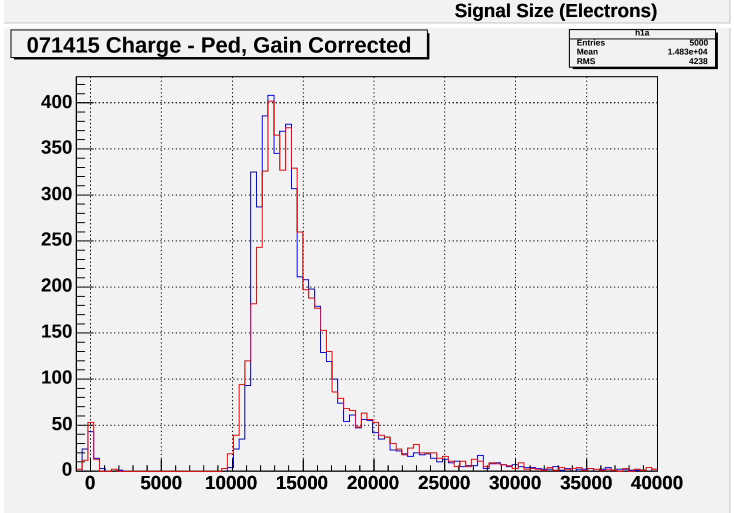
- Q_{MP} = 8500-9000e
- Mean Charge = 11300e

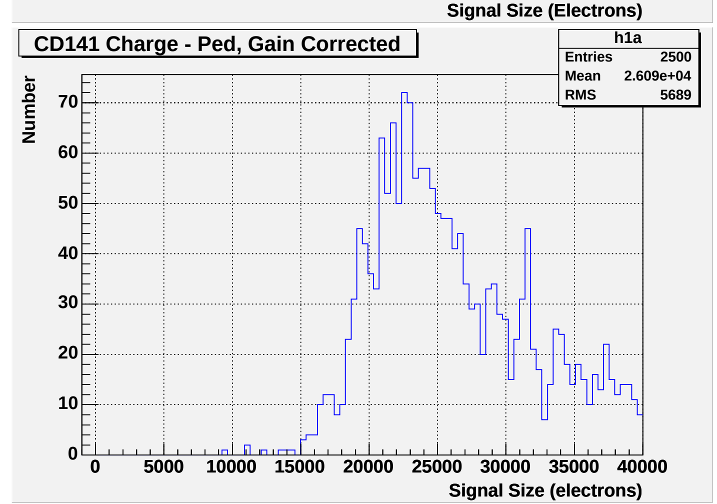
- Source data well separated from 0
- Collection Distance now ≈ 250-300μm
- Most Probable Charge now ≈ 8000-9000e
- 99% of PH distribution above 4000e
- FWHM/MP ≈ 0.95 — Si has ≈ 0.5

scCVD Diamond Measured with a ^{90}Sr Source:



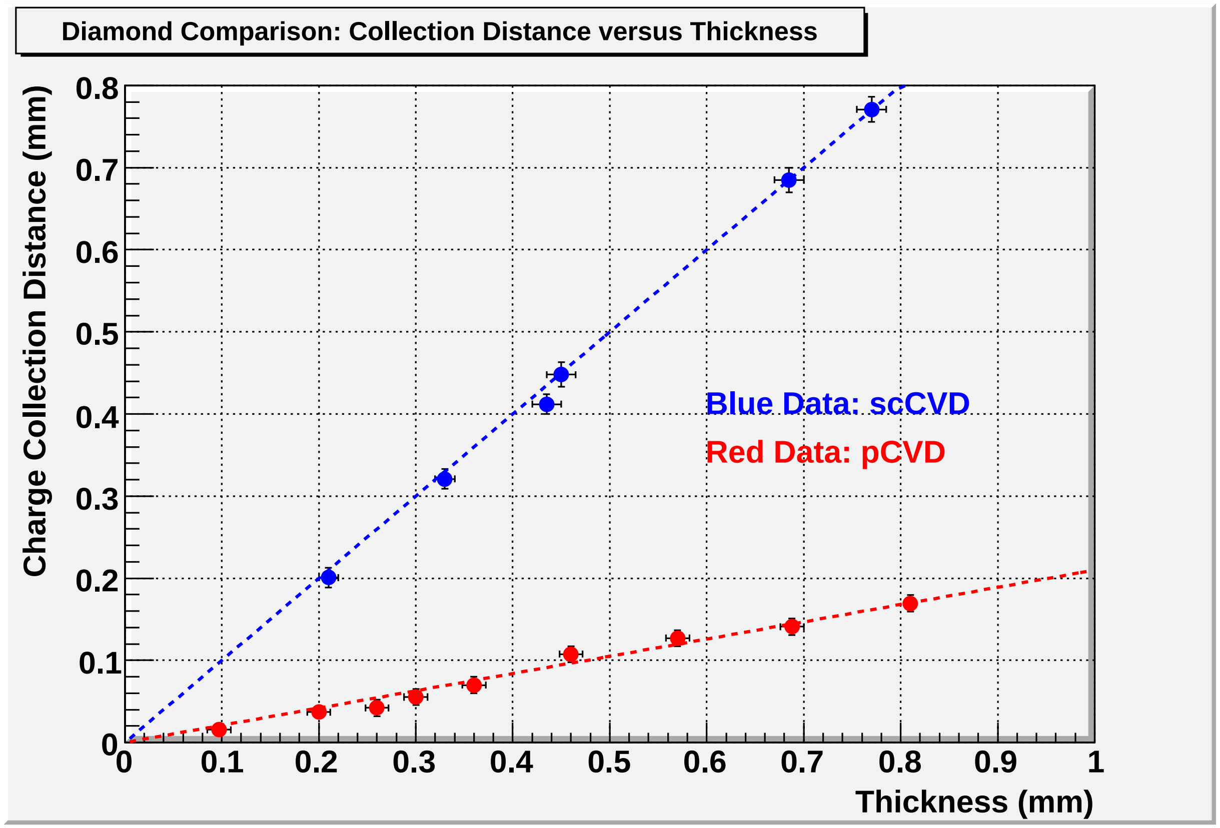






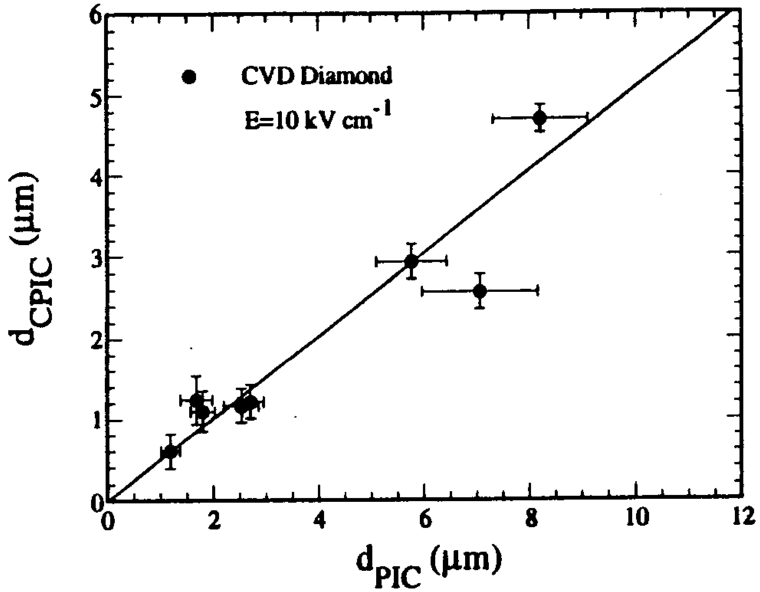
Pulse height spectrum of various scCVD diamonds (t=210, 320, 435, 685 μm)

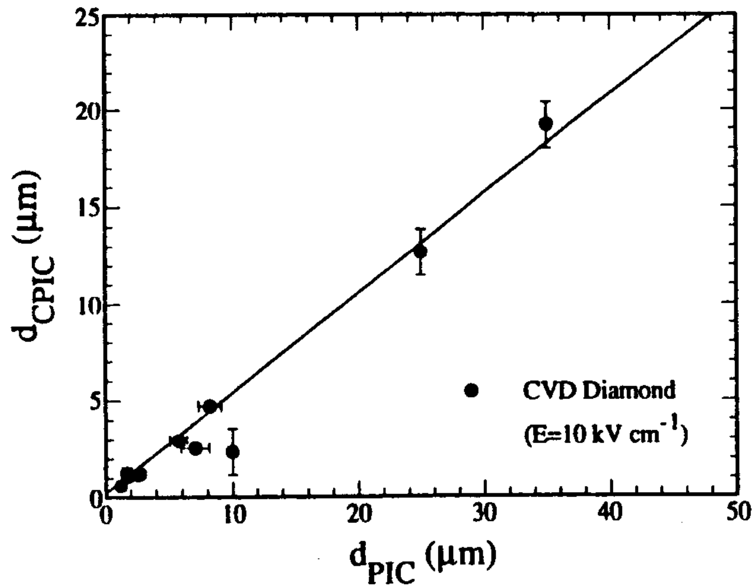
Charge Collection Distance versus Thickness



- The collection distance for both scCVD and pCVD is linear with thickness
- High quality scCVD diamond can collect full charge for thickness 880μm
- Width of scCVD Landau distribution is $\approx 1/2$ that of silicon, $\approx 1/3$ that of pCVD diamond

The Linear Model [Plano *et al.*, Appl. Phys. Lett 64 (1994) 193, Zhao Ph.D. Thesis (1994)]



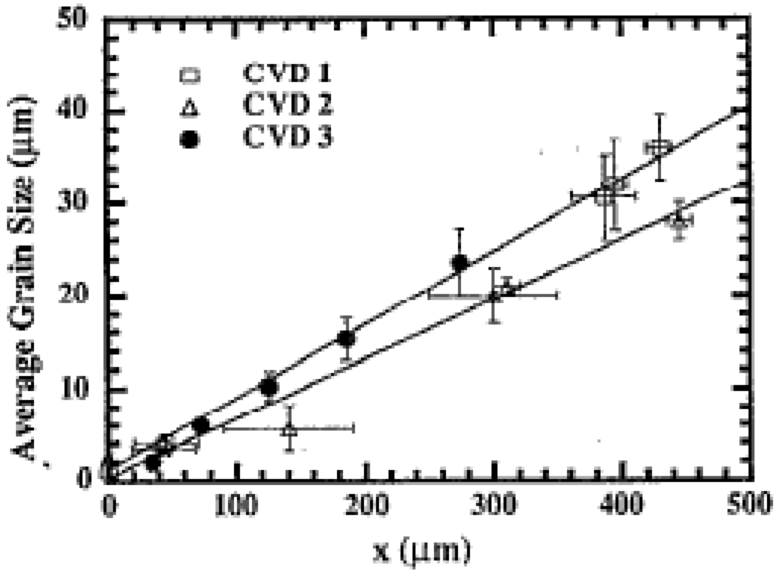


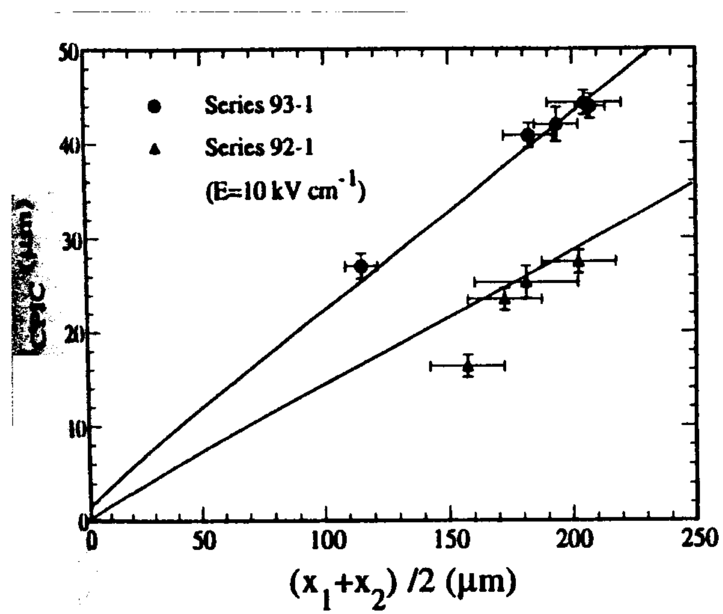
- Compare Growth Surface (PIC) with Bulk Average (CPIC) collection distance
- Growth Surface has twice the collection distance of bulk!
- Substrate has 0 collection distance!
- Implies linear growth → convert to grown thickness

All high quality pCVD material exhibits this principle!

Charge Collection - The Linear Model

The Linear Model - Grain Size, Quality

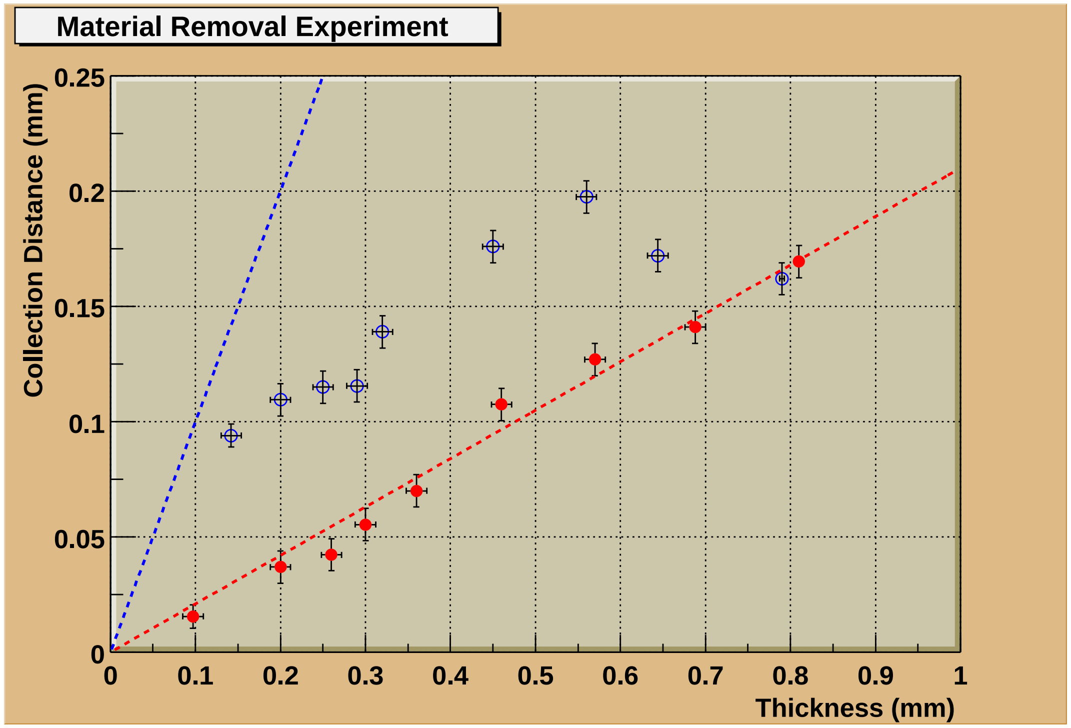


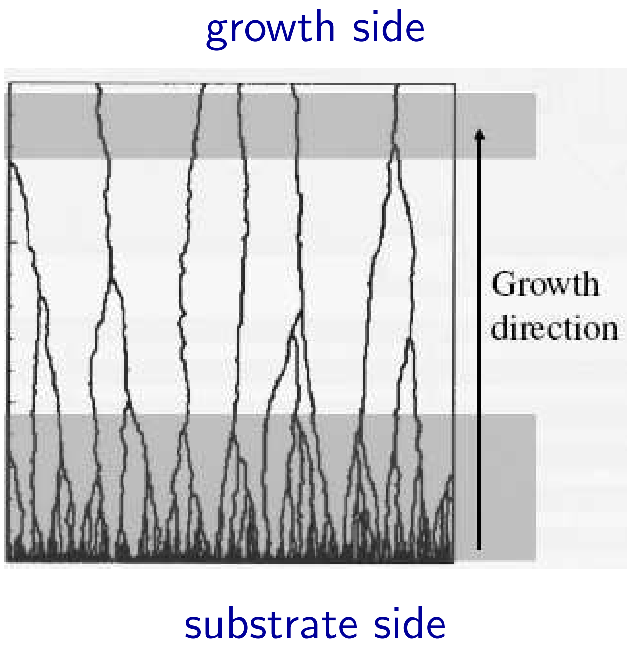


- Etch surface to expose grains
- Count grains per unit area for various thickness material
- Within a given set of growth parameters → grain size grows linearly with thickness
- Within a given set of growth parameters → collection distance grows linearly with thickness

All high quality pCVD material exhibits this principle!

The Linear Model - Electronic Properties





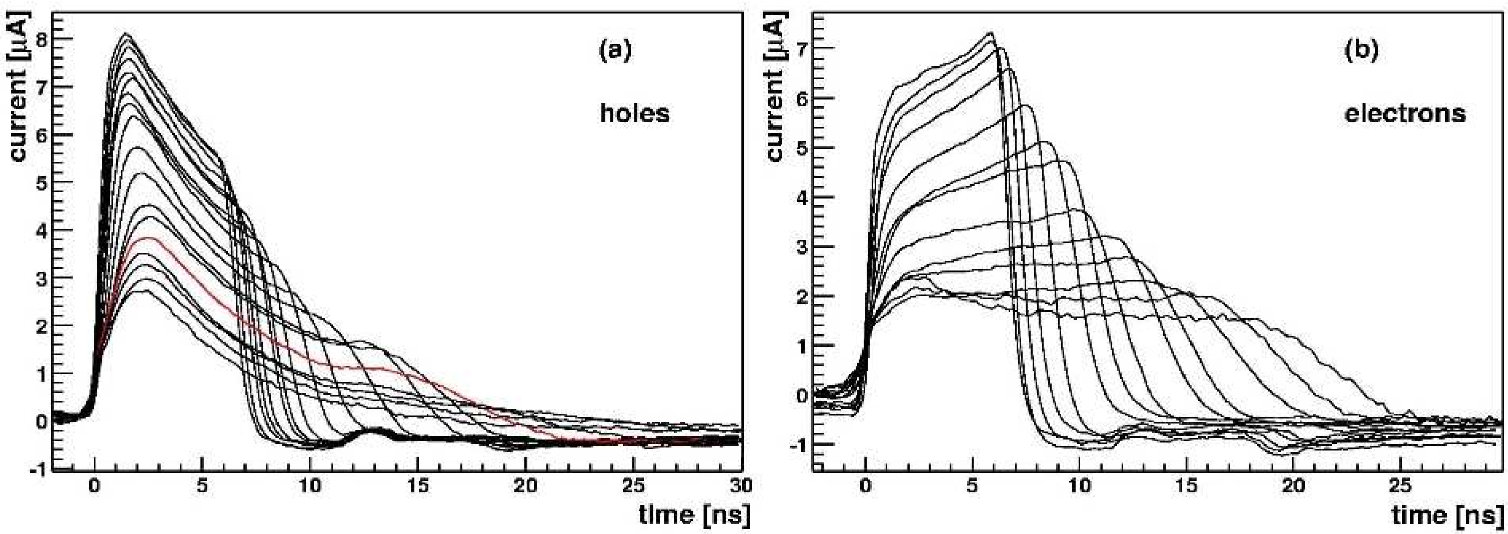
- Use 2 samples from the same wafer
- Mark the substrate side on one, the growth side on the other
- Remove material from the unmarked side, measure ccd

All high quality pCVD material uses this processing principle!

Charge Collection - Drift Velocity and Lifetime

Transient Current Measurements (TCT)

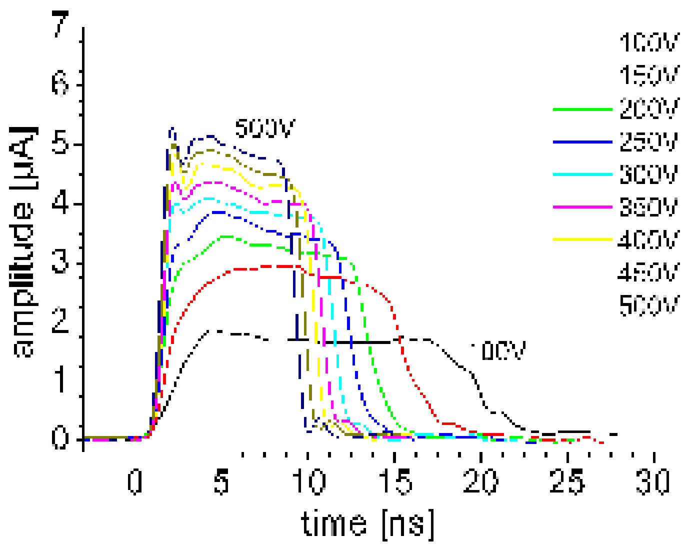
- Measure charge carrier properties separately for electron and holes
- Use α-source (Am241) to inject charge
  - penetration $\approx$ 14 μm (thickness of diamonds $\approx$ 470 μm)
  - use positive and negative applied voltage
- Amplify ionization current

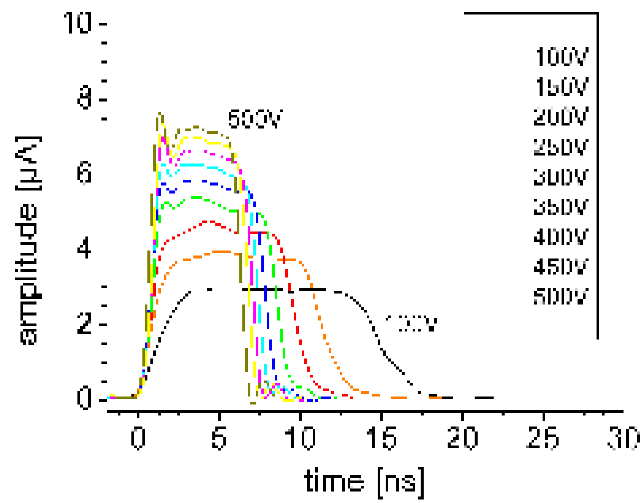


Extracted parameters: Transit time, velocity, lifetime, space charge, pulse shape, charge.

H. Pernegger, *et al.*, "Charge-carrier Properties in Synthetic Single-crystal Diamond measured with the Transient-current Technique", J. Appl. Phys. 97, 073704 (2005)

Drift Velocity and Lifetime:

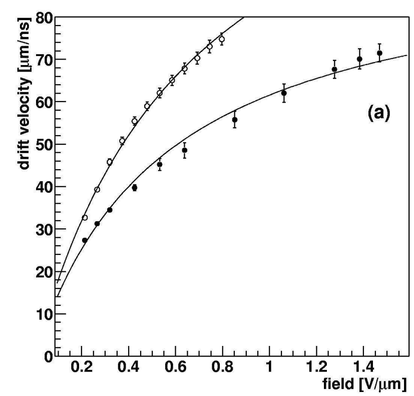




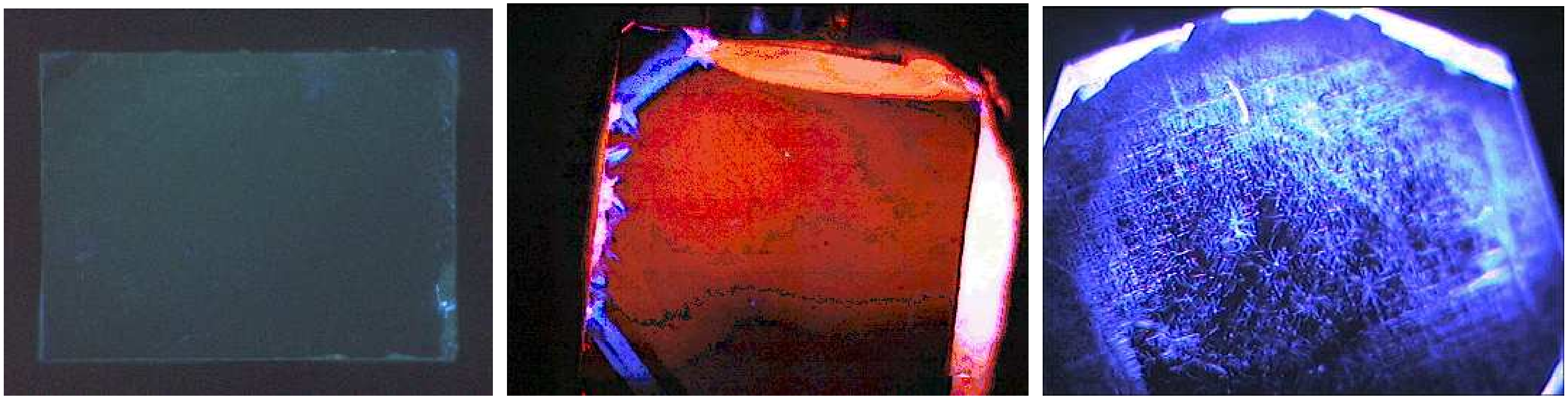
- Average drift velocity for electrons and holes: $v_{e,h} = d/t_c$
- Extract μ_0 and saturation velocity: $v = \frac{\mu_0 E}{1+\mu_0 E/v_s}$
- Hole mobility (speed) larger than electron mobility (speed)!

  $\mu_{0_e} = 1714\ \text{cm}^2/\text{Vs} \qquad v_{s_e} = 0.96 \times 10^7\ \text{cm/s}$

  $\mu_{0_h} = 2064\ \text{cm}^2/\text{Vs} \qquad v_{s_h} = 1.41 \times 10^7\ \text{cm/s}$
- From the drift velocity deduce the lifetimes > 35 ns $\rightarrow >>$ transit time so charge trapping not the issue



Impurities, Defects and Dislocations: Photo-Luminescence Measurements



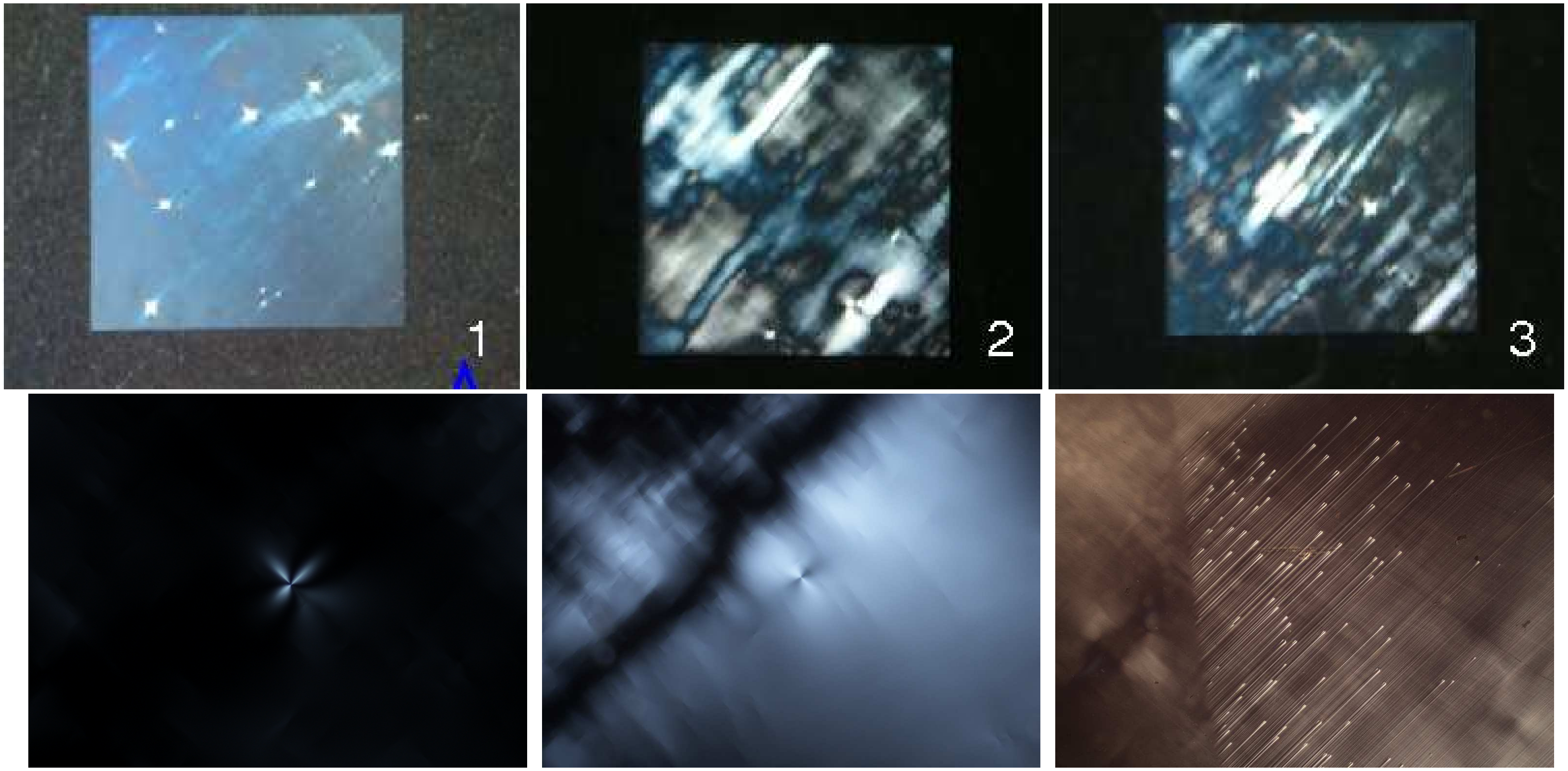
Left Image: High purity, no nitrogen, no dislocations.

Middle Image: Contains nitrogen - NV centre, 575 nm PL.

Right Image: Contains surface dislocations, broad band blue PL.

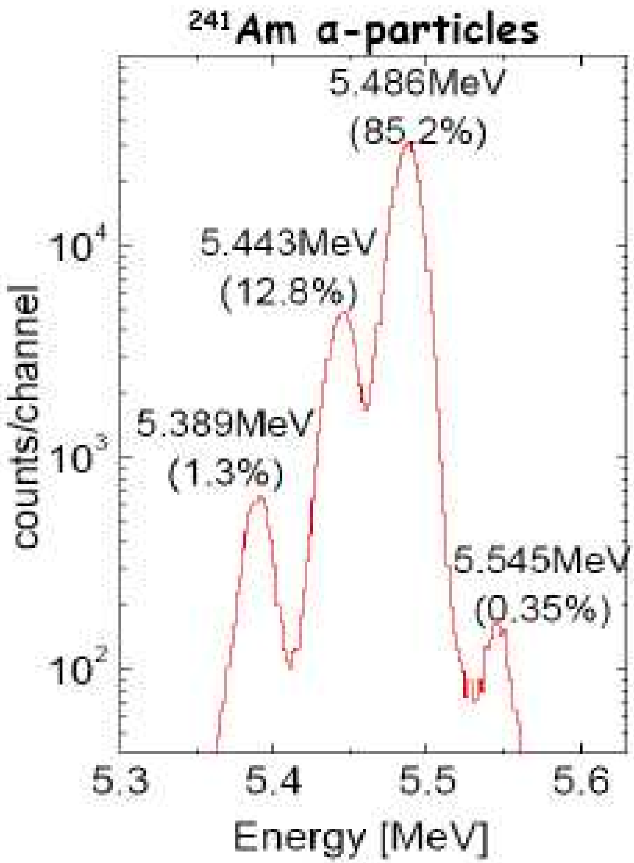
May be able to unravel the compexity of the CVD process!

Impurities, Defects and Dislocations: Crossed Polarizer, DIC, ...



- Find “good” and “bad” scCVD material
- Charge collection properties correlated with defects, dislocations
- Charge collection properties correlated with surface damage
- These measurements help in the sorting of scCVD material quality

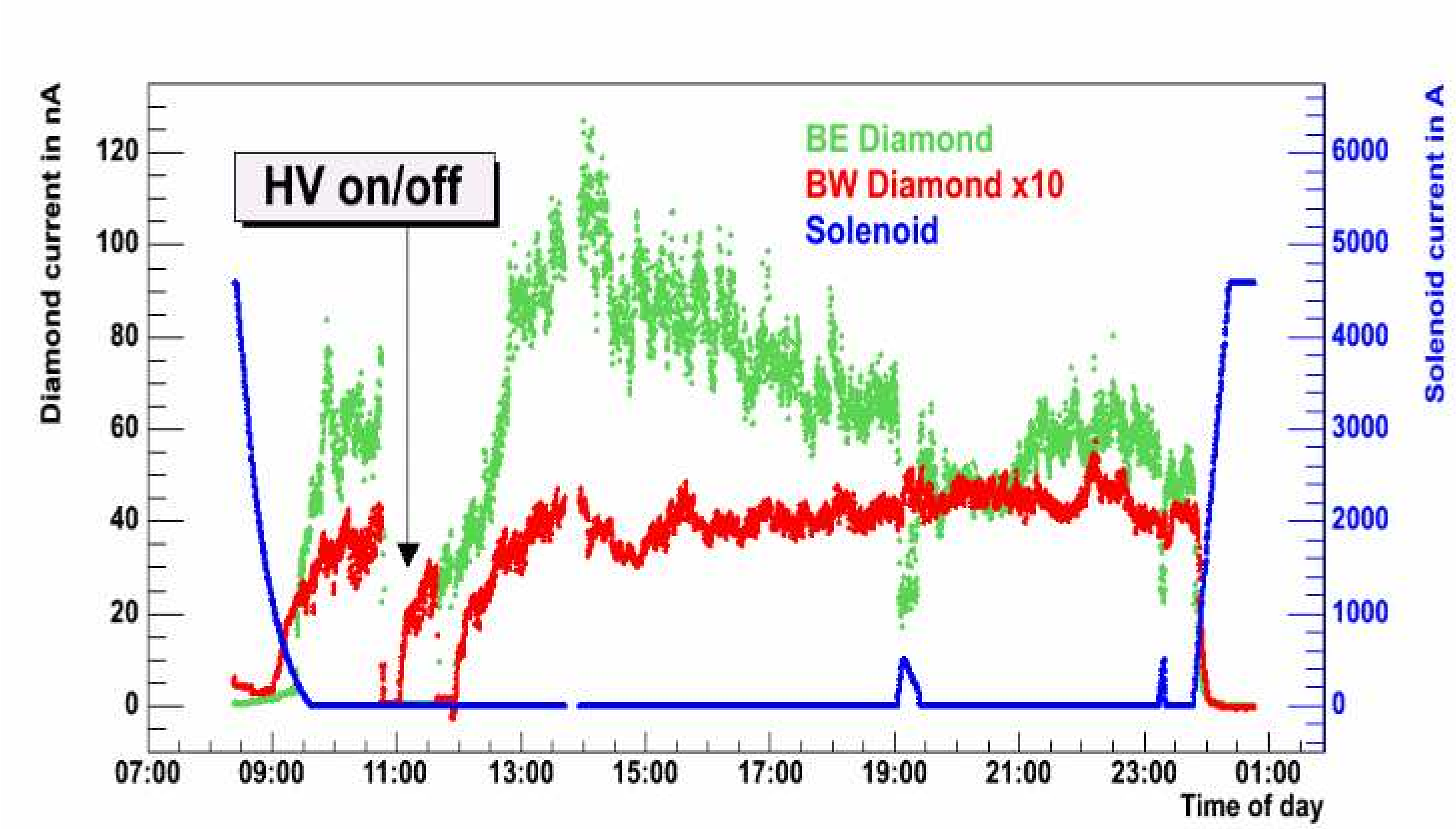
Energy Resolution:



- FWHM: 17keV @ 5.4MeV → spectroscopic material

Erratic Dark Currents:

- First observed in BaBar when the magnetic field was inadvertently turned off
- Diamond detector current usually small ($\sim$ nA)
- Detector currents increased dramatically after magnetic trip

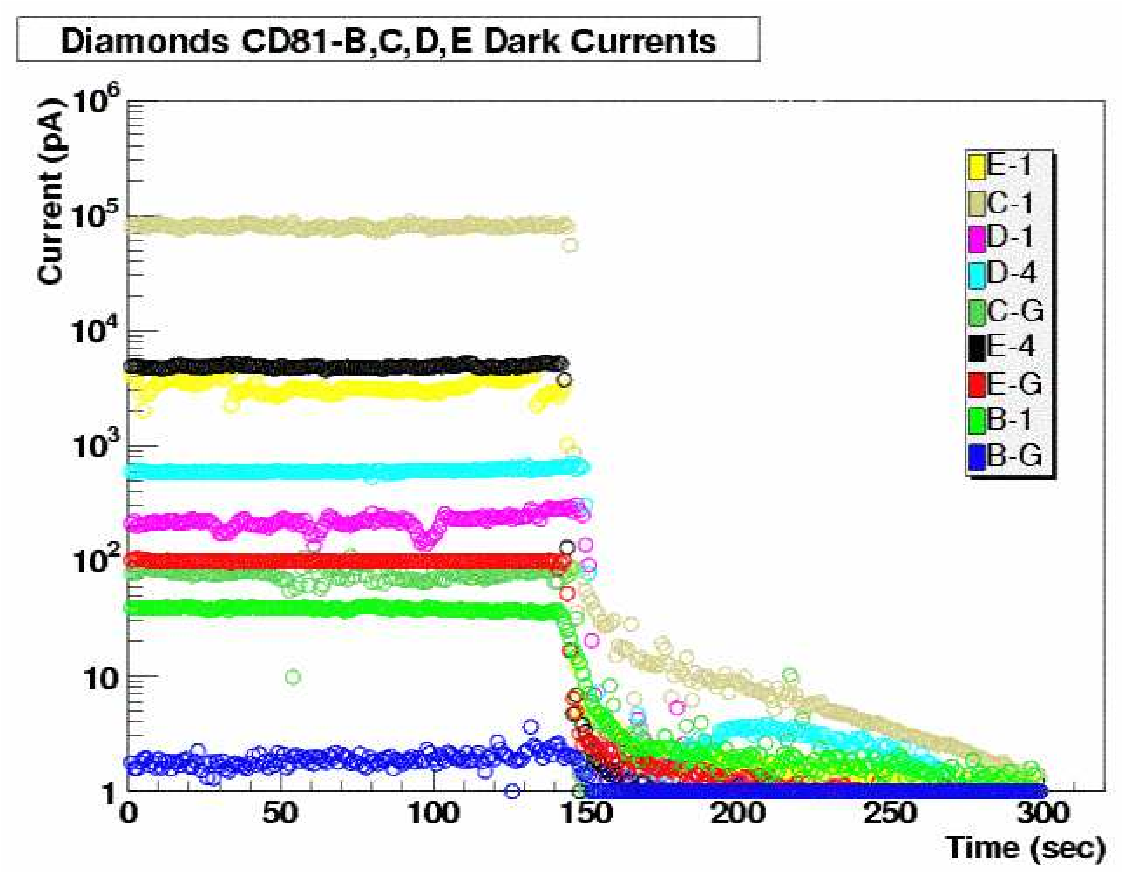


Erratic Dark Currents! Missed because they are hard to induce!

Diamond Current Increases as Magnetic Field goes Off ...

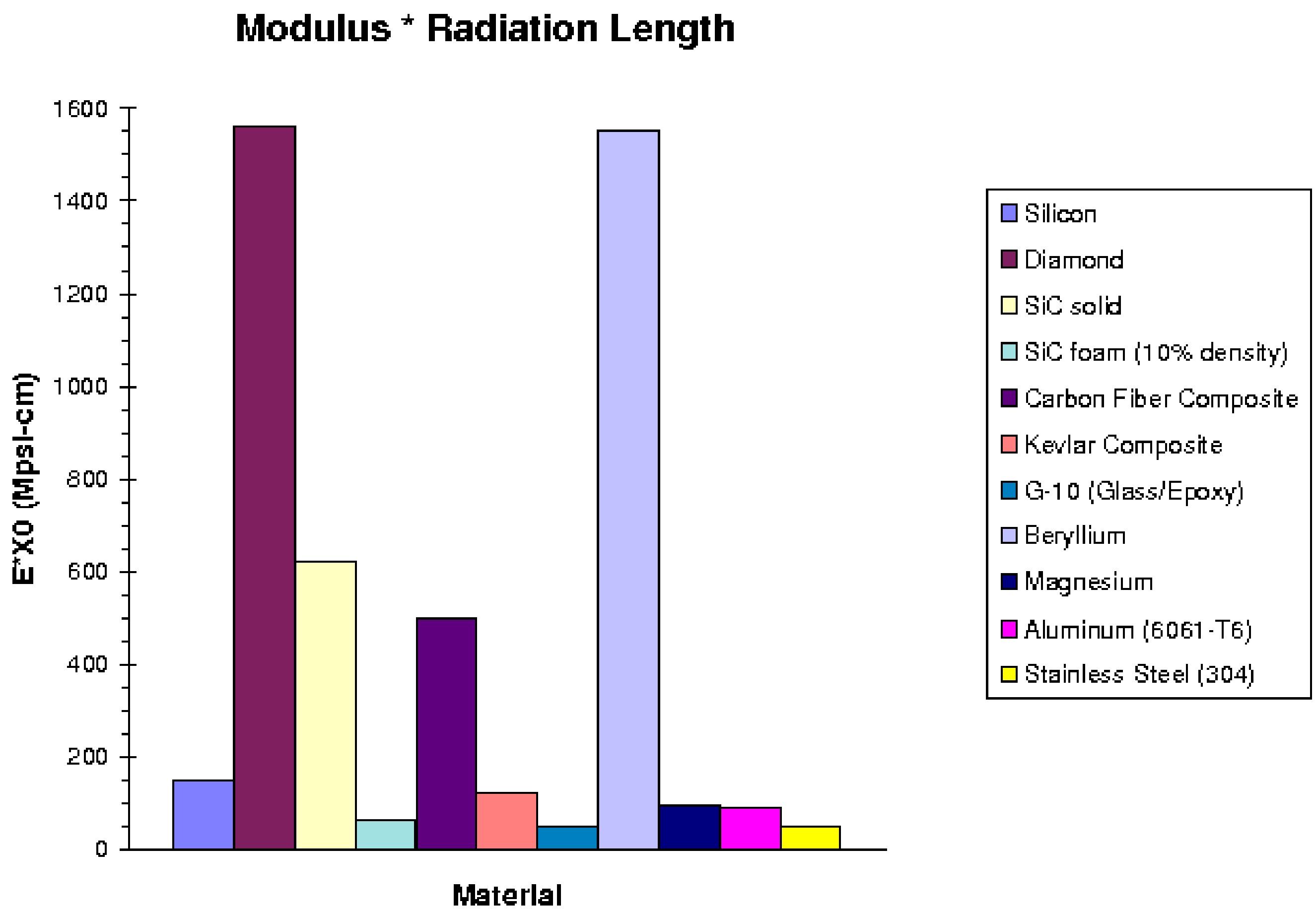
Set up lab experiment (voltage,time) → current is localized!

All Go Away in Magnetic Field (0.5T)



Erratic Dark Currents seen in BaBar, CDF, ATLAS and CMS. Understood?

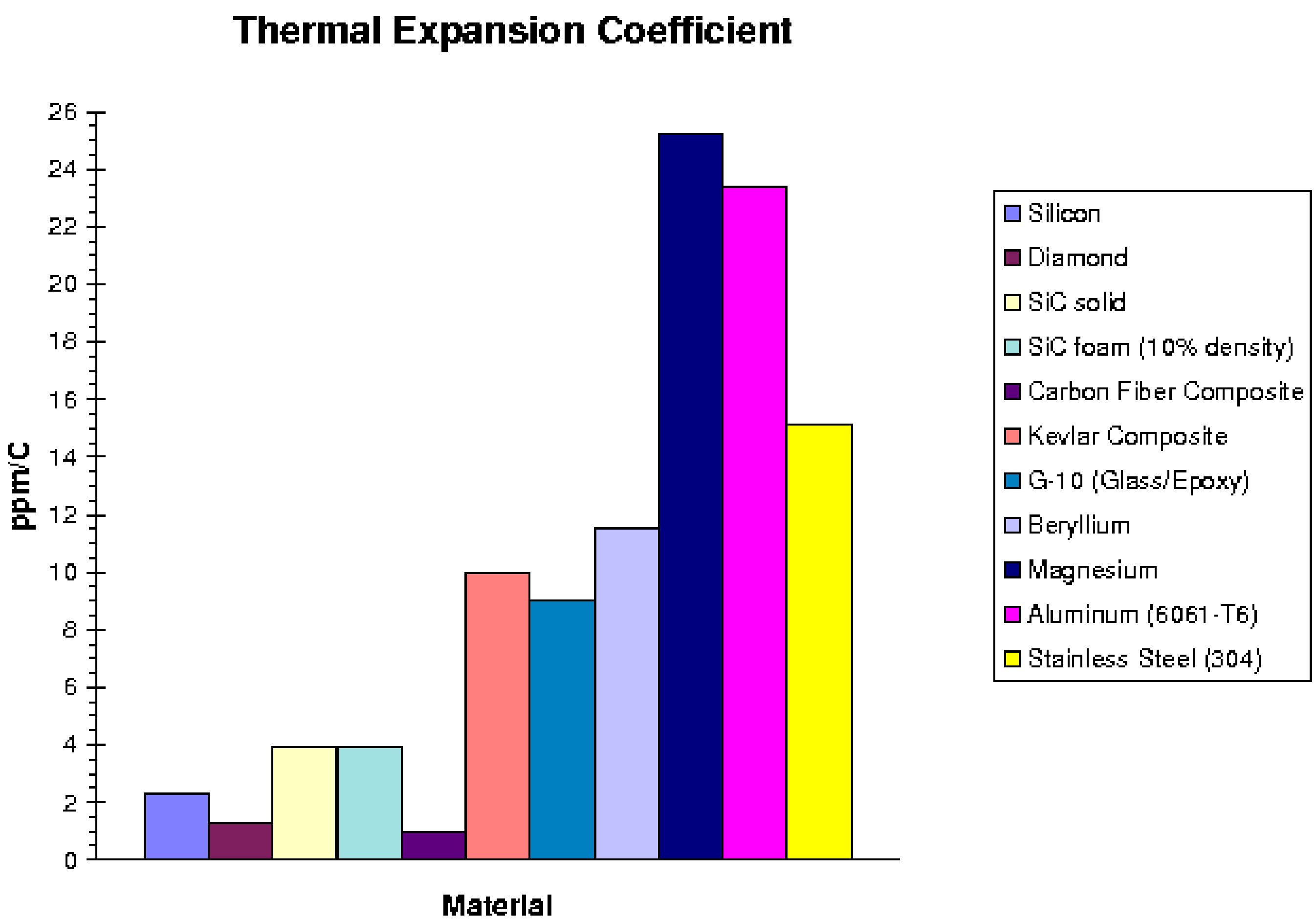
Strength to Weight Ratio:



- High strength to weight ratio.

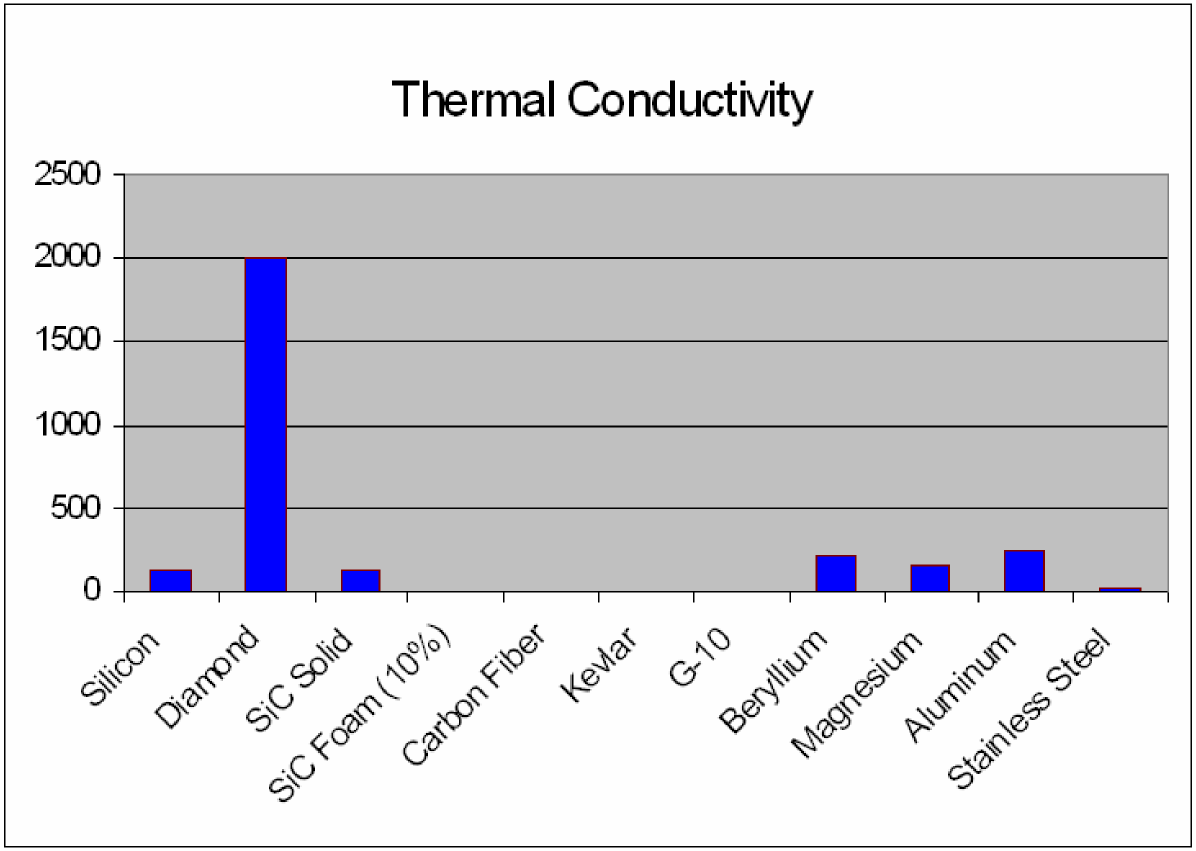
Other Properties

Thermal Expansion:

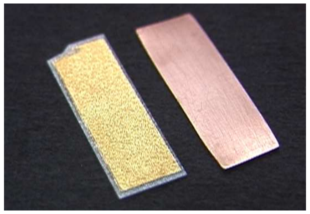


- Small coefficient of thermal expansion.

Thermal Conductivity:



- Thermal conductivity $5\times$ larger than copper at room temperature,
- Movie - Ice



Summary of Electronic and Mechanical Properties

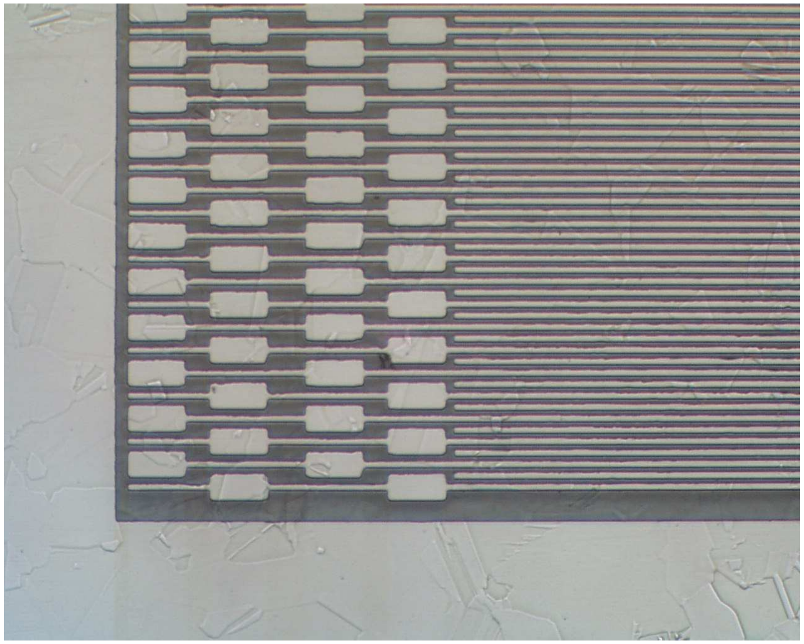
CVD Diamond Properties for Detector Builders:

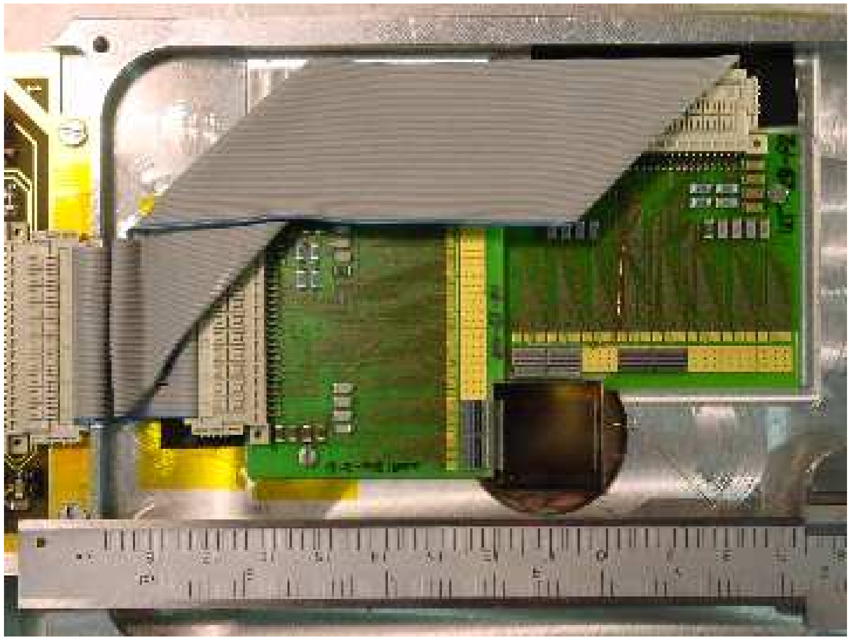
- MIP produces on average 3600e/100μm of material
- All pCVD and some scCVD has traps (defects) $\rightarrow$ diamond "pumps"
- Collection distance is the mean distance the eh pair move apart $\rightarrow$ signal
- Collection distance near the substrate side is essentially 0 $\rightarrow$ traps
- The electronic properties get better linearly with thickness grown
- To make pCVD detector $\rightarrow$ grow thick and remove material from substrate/bad side
- The measured charge saturates around E=1-2V/μm
- Little or no leakage current at E=1V/μm
- If measuring current - watch for Erratic Dark Currents/use low HV/use magnetic field
- The collection distance for pCVD around 250-300μm
- Charge collection time is fast $<$10ns for 500μm thick material
- Must select to get good material $\rightarrow$ defects, sub-surface damage, etc.
- scCVD material can have spectroscopic Energy resolution - not yet true for pCVD
- CVD diamond strength to weight ratio large - similar to Be
- CVD diamond thermal expansion small - similar to carbon fiber
- CVD diamond thermal conductivity large - no thermal runaway

Radiation Hardness

- binding energy, displacement energy
- charge collection distance
- mean free path
- elastic, inelastic, total cross section

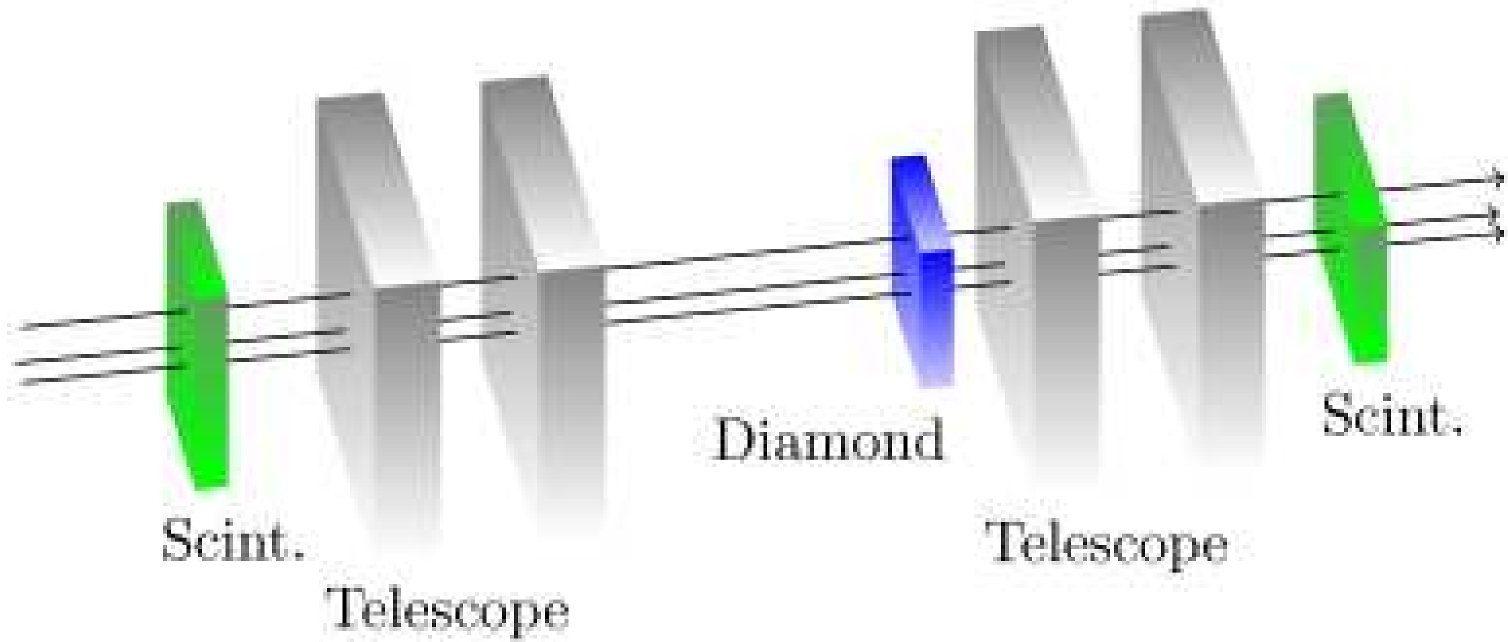
pCVD Diamond Trackers:





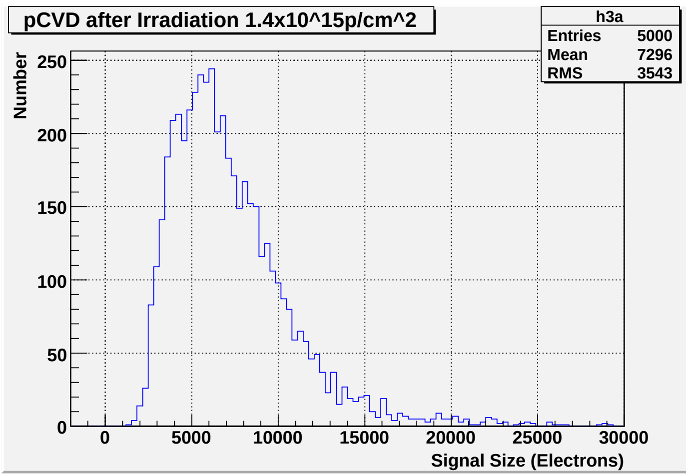
- Patterning the diamond $\rightarrow$ pads, strips, pixels!
- Successfully made double-sided devices; $\sim$edgeless.
- Segmented devices critical in radiation studies - charge and position.

Test Beam Setup



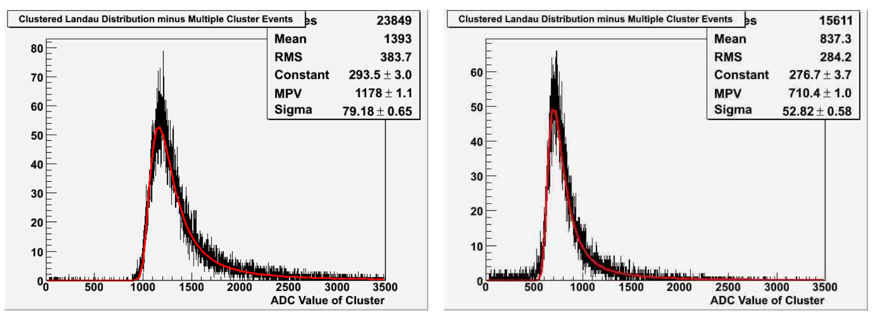
Irradiated devices characterized in test beams - transparent or unbiased prediction from telescope.

Polycrystalline CVD (pCVD) Diamond irradiations at 1.4x10^{15}



- Application is pixel detectors
- At the LHC, Thresholds will be $\sim (1000e)$
- PH distributions look good after irradiation of 1.4x10^{15}p/cm^2, $\epsilon > 99\%$

Single Crystal CVD (scCVD) Diamond irradiations at 1.5x10^{15}



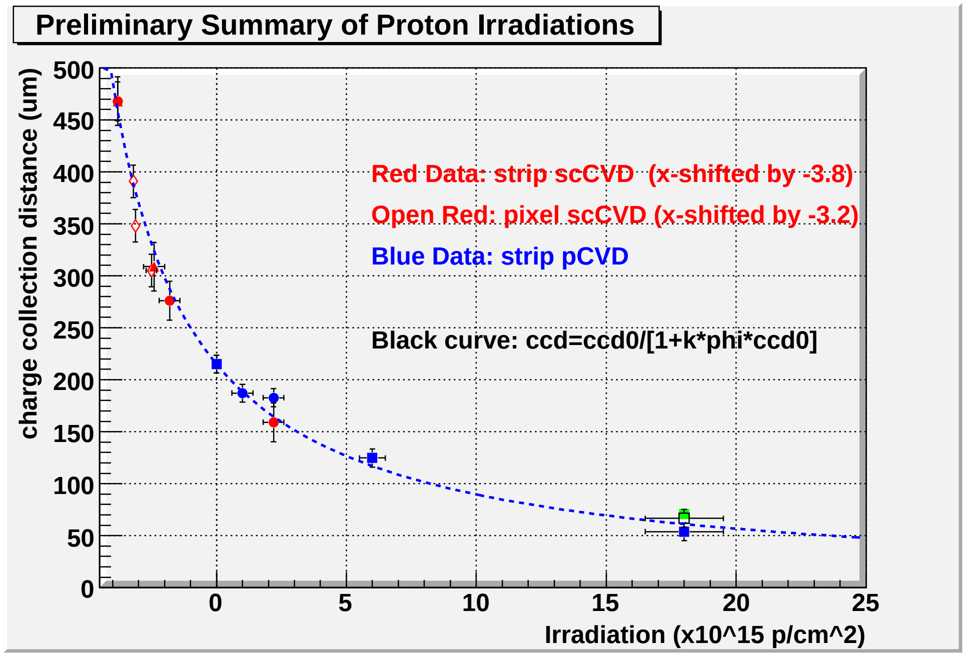
- PH distributions look narrow before and after irradiation
- PH distributions after 1.5x10^{15}p/cm^2 $\rightarrow \epsilon > 99\%$.

Proton Irradiation Summary - CERN PS 24 GeV protons:

Damage equation:

$$\frac{1}{\text{ccd}} = \frac{1}{\text{ccd}_0} + k\phi$$

- ccd_0 initial traps in material
- k damage constant
- ϕ fluence
- Applicable when ccd $<<$ t



Irradiation results up to 1.8×10^{16} p/cm^2 (∼500Mrad)

Test beam data shown - source overestimates damage

pCVD and scCVD diamond follow the same damage curve

Larger ccd_0 performs better at any fluence

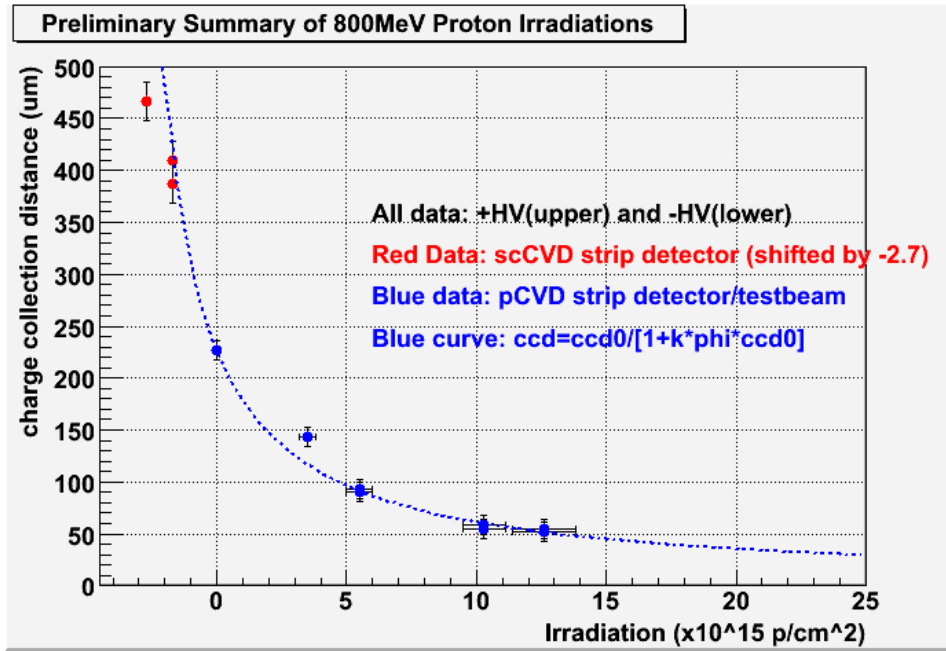
Proton damage understood

Proton Irradiation at Lower Energy - LANL 800 MeV protons:

Damage equation:

$$\frac{1}{\mathrm{ccd}} = \frac{1}{\mathrm{ccd}_0} + k\phi$$

- ccd_0 initial traps in material
- k damage constant
- ϕ fluence
- Applicable when ccd $<<$ t



New results from low energy irradiation

Irradiation results up to 1.3×10^{16} p/cm^2

Test beam data shown - source overestimates damage

Same form of damage curve: $1/\mathrm{ccd}=1/\mathrm{ccd}_0 + k\,\phi$

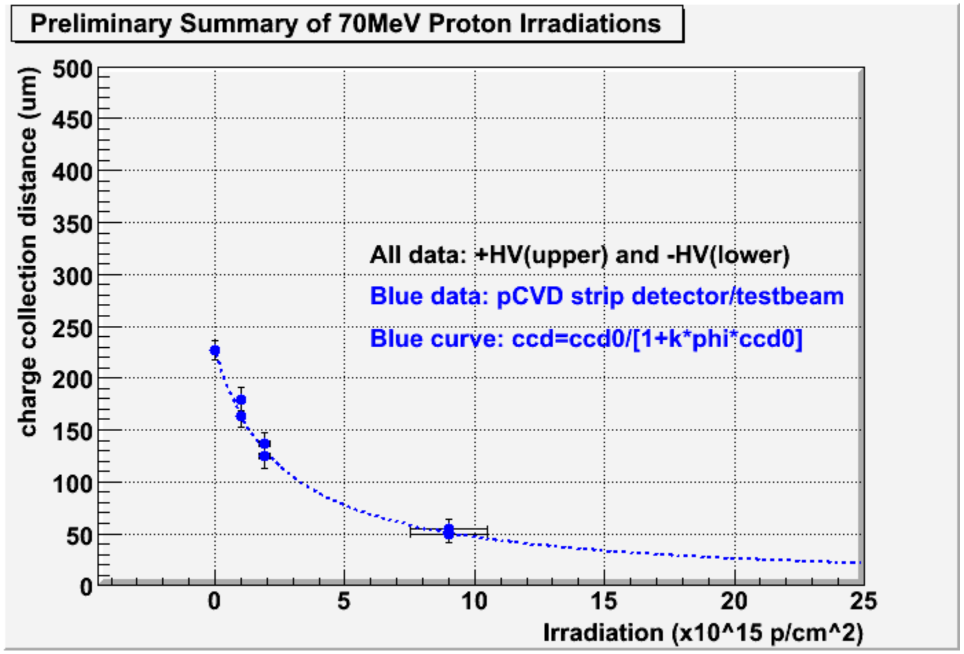
800 MeV protons 1.6-1.8$\times$ more damaging than 24 GeV proton

Proton Irradiation at Lower Energy - Sendai/CYRIC 70 MeV protons:

Damage equation:

$$\frac{1}{\mathrm{ccd}} = \frac{1}{\mathrm{ccd}_0} + k\phi$$

- ccd_0 initial traps in material
- k damage constant
- ϕ fluence
- Applicable when ccd $<<$ t



New results from low energy irradiation

Irradiation results up to 0.9×10^{16} p/cm^2

Test beam data shown - source overestimates damage

Same form of damage curve: 1/ccd=1/ccd$_0$ +k ϕ

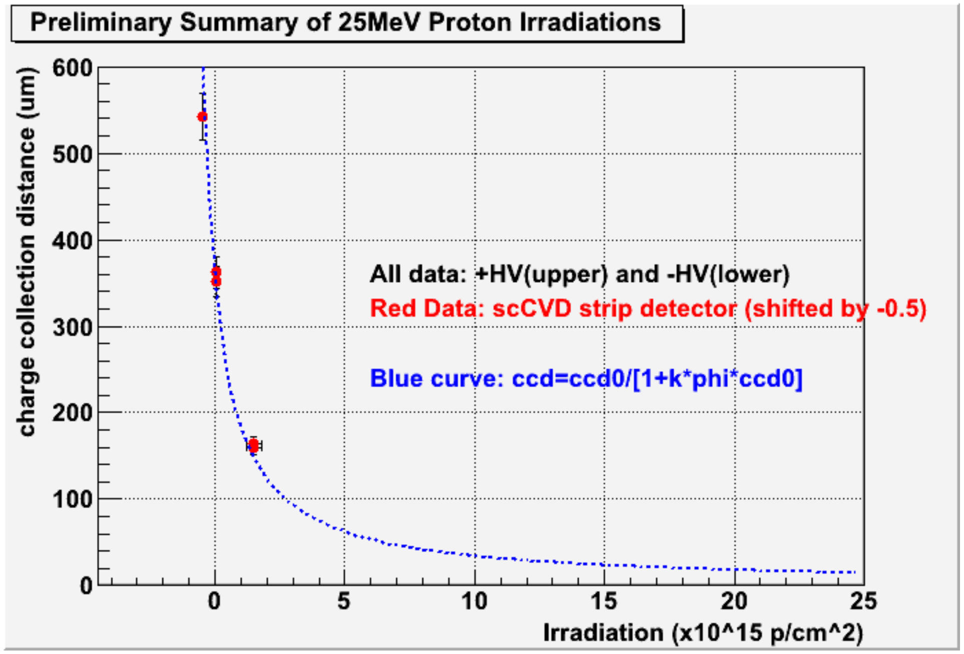
70 MeV protons 2.5-2.8$\times$ more damaging than 24 GeV proton

Proton Irradiation at Lower Energy - 25 MeV protons:

Damage equation:

$$\frac{1}{\mathrm{ccd}} = \frac{1}{\mathrm{ccd}_0} + k\phi$$

- ccd_0 initial traps in material
- k damage constant
- ϕ fluence
- Applicable when ccd $<<$ t



New results from low energy irradiation

Irradiation results up to 0.3×10^{16} *p/cm*^{2}

Test beam data shown - source overestimates damage

Same form of damage curve: 1/ccd=1/ccd$_0$ *+k* ϕ

25 MeV protons 4-5$\times$ *more damaging than 24 GeV proton*

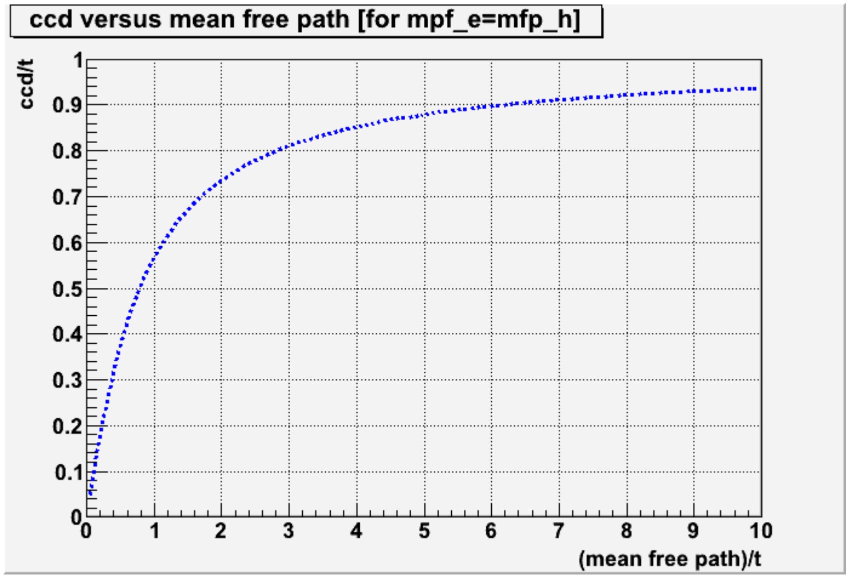
Charge Collection Distance versus Mean Free Path

- For pCVD ccd $<$ thickness; however for scCVD ccd $\sim$ thickness. To compare must use correct form of damage equation ccd $\rightarrow$ mfp

$$\frac{1}{mfp} = \frac{1}{mfp_0} + k\phi$$

- Collection Distance coincides with Mean Free Path when ccd $<<$ t
- Collection Distance is raw data $\rightarrow$ no correction.
- Mean Free Path is correct theory but must correct data $\rightarrow$ assumptions

$$\frac{ccd}{t} = \sum_i \frac{mfp_i}{t}\left[1 - \frac{mfp_i}{t}\left(1 - e^{-\frac{t}{mfp_i}}\right)\right]$$

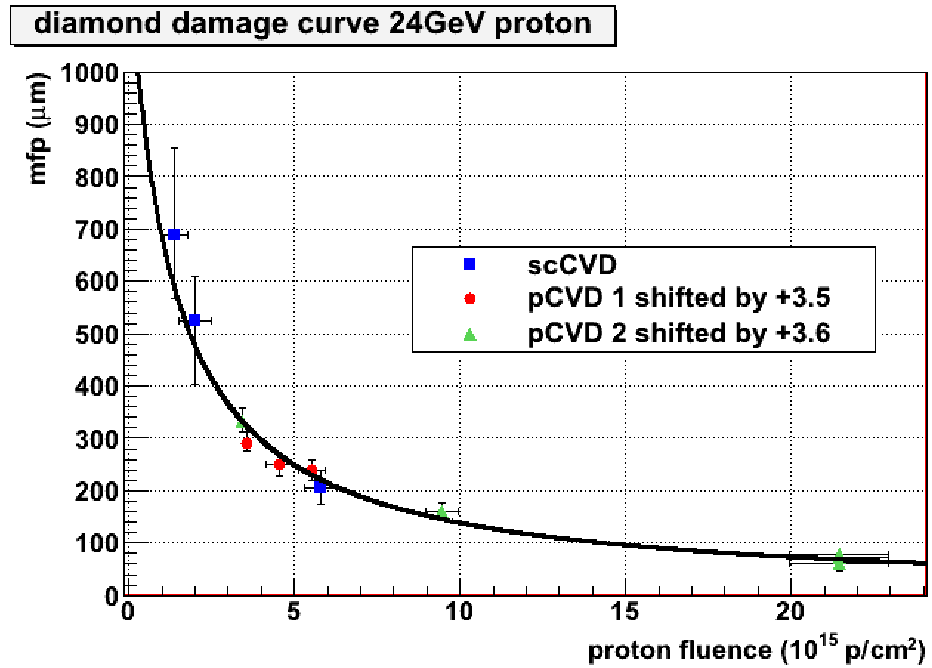


Proton Irradiation Summary - CERN PS 24 GeV protons:

Damage equation:

$$\frac{1}{\mathrm{mfp}} = \frac{1}{\mathrm{mfp}_0} + k\phi$$

- mfp_0 initial traps in material
- k damage constant
- ϕ fluence
- Assume $\mathrm{mfp}_e = \mathrm{mfp}_h$



Irradiation results up to 1.8×10^{16} p/cm^2 (~500Mrad)

Test beam data shown - source overestimates damage

pCVD and scCVD diamond follow the same damage curve $k_{scCVD} = k_{pCVD}$

Larger mfp_0 performs better at any fluence

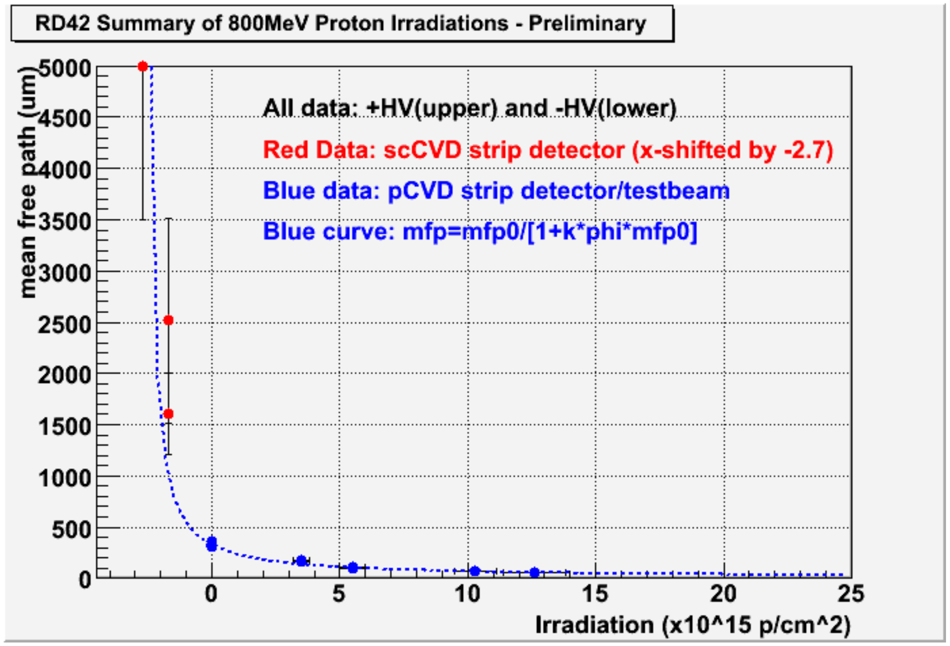
Proton damage understood, $k = 0.65 - 0.70 \times 10^{-18} \mu m^{-1} cm^2$

Proton Irradiation at Lower Energy - LANL 800 MeV protons:

Damage equation:

$$\frac{1}{\mathrm{mfp}} = \frac{1}{\mathrm{mfp}_0} + k\phi$$

- mfp_0 initial traps in material
- k damage constant
- ϕ fluence
- Assume $\mathrm{mfp}_e = \mathrm{mfp}_h$



New results from low energy irradiation

Irradiation results up to 1.3×10^{16} p/cm^2

Test beam data shown - source overestimates damage

Same damage curve: 1/mfp=1/mfp$_0$ +k $\phi \rightarrow k = 1.2 \times 10^{-18} \mu m^{-1} cm^2$

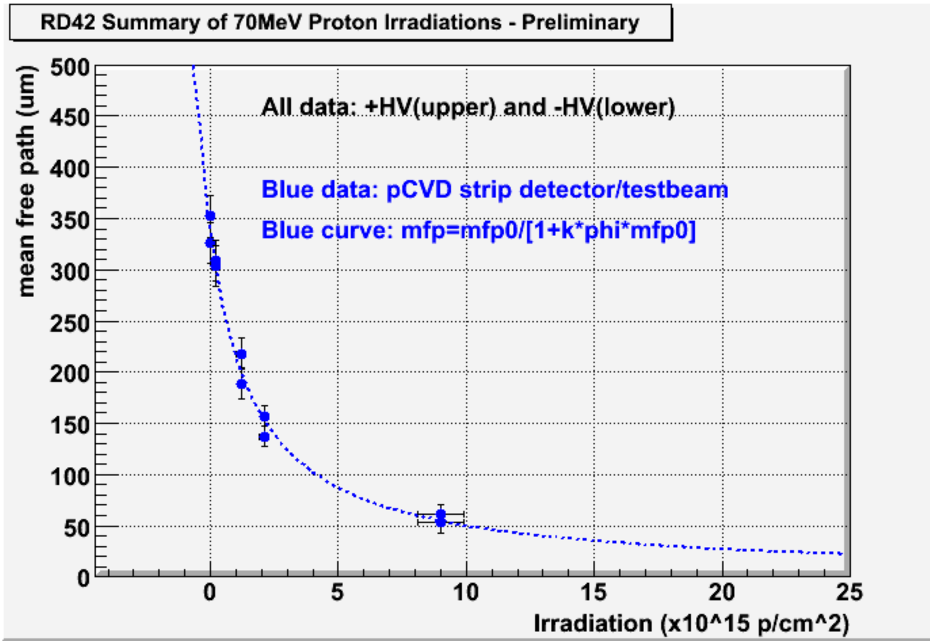
800 MeV protons 1.6-1.8$\times$ more damaging than 24 GeV proton

Proton Irradiation at Lower Energy - Sendai/CYRIC 70 MeV protons:

Damage equation:

$$\frac{1}{\text{mfp}} = \frac{1}{\text{mfp}_0} + k\phi$$

- mfp_0 initial traps in material
- k damage constant
- ϕ fluence
- Assume $\text{mfp}_e = \text{mfp}_h$



New results from low energy irradiation

Irradiation results up to 0.9×10^{16} p/cm^2

Test beam data shown - source overestimates damage

Same damage curve: 1/mfp=1/mfp$_0$ +k $\phi \rightarrow k = 1.7 \times 10^{-18} \mu m^{-1} cm^2$

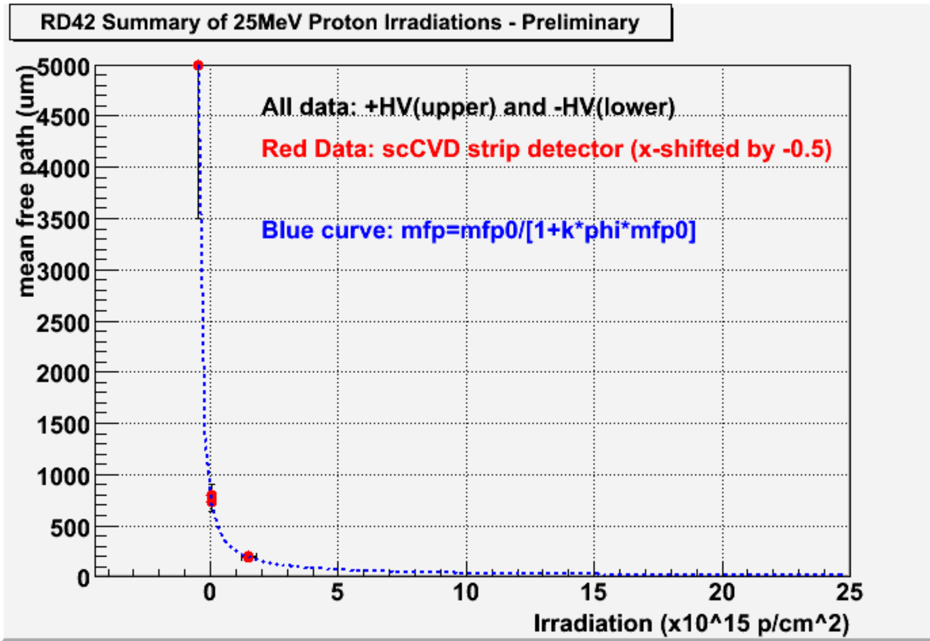
70 MeV protons 2.5-2.8$\times$ more damaging than 24 GeV proton

Proton Irradiation at Lower Energy - 25 MeV protons:

Damage equation:

$$\frac{1}{\mathrm{mfp}} = \frac{1}{\mathrm{mfp}_0} + k\phi$$

- mfp_0 initial traps in material
- k damage constant
- ϕ fluence
- Assume $\mathrm{mfp}_e = \mathrm{mfp}_h$



New results from low energy irradiation

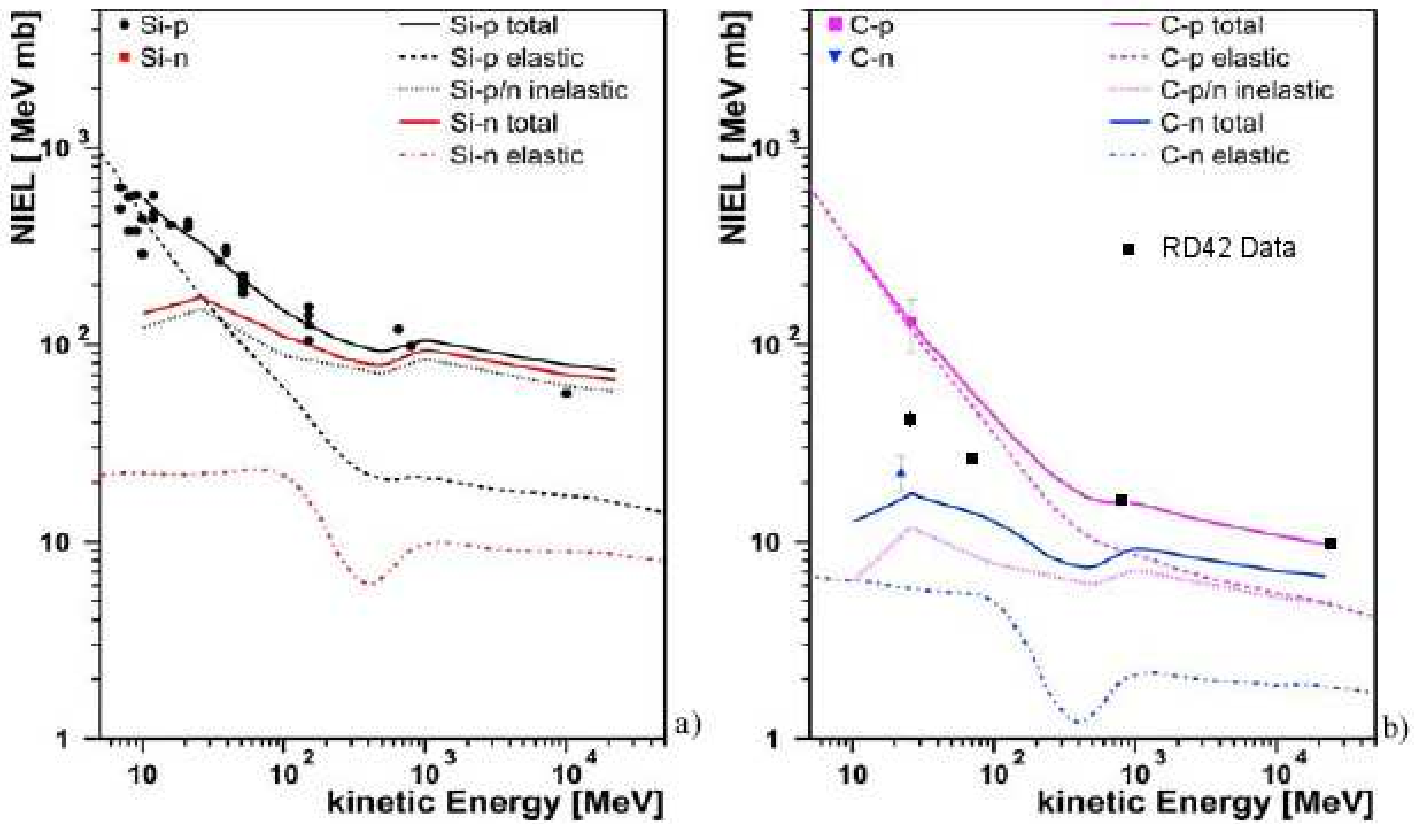
Irradiation results up to 0.3×10^{16} p/cm^2

Test beam data shown - source overestimates damage

Same damage curve: 1/mfp=1/mfp$_0$ +k $\phi \rightarrow k = 2.6 \times 10^{-18} \mu m^{-1} cm^2$

25 MeV protons 4-5$\times$ more damaging than 24 GeV proton

Summary of Proton Irradiations:

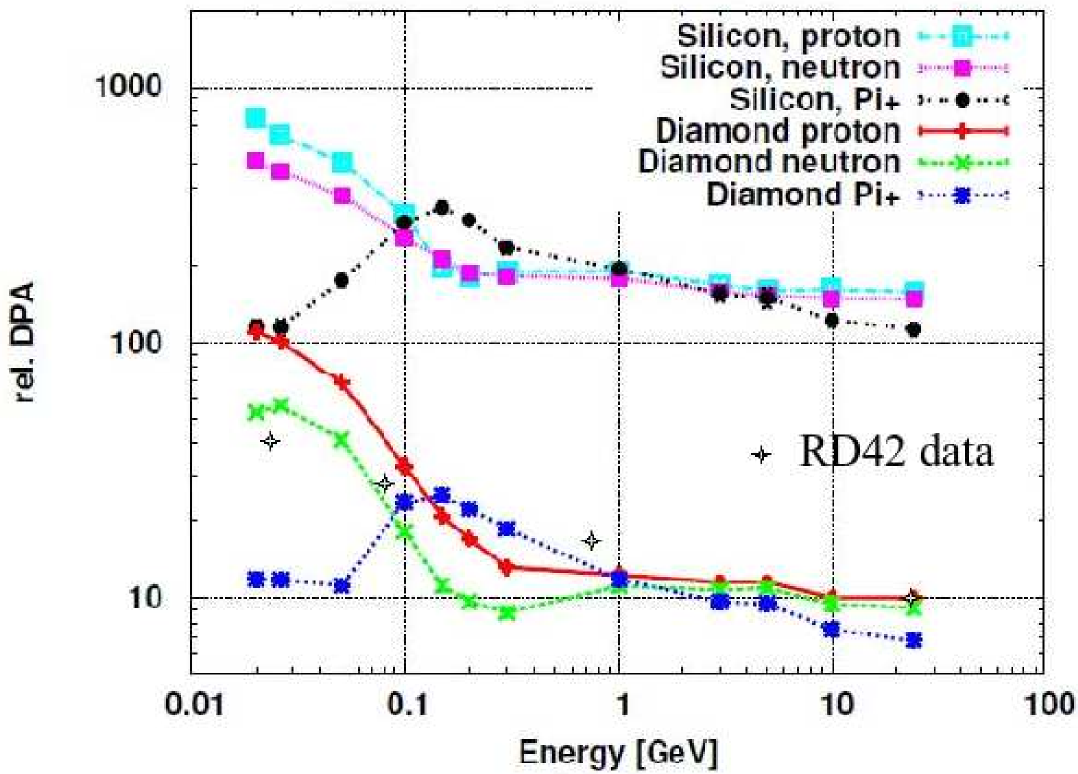


New results from low energy irradiations.
Deviation from calculated NIEL at low energy.
NIEL violation? or is theory incorrect? Use FLUKA-DPA scaling.

Summary of Proton Irradiations:

DPA based on Displacement Energy D: ∼ 42eV; Si: ∼ 25eV

graph from S. Mueller Thesis



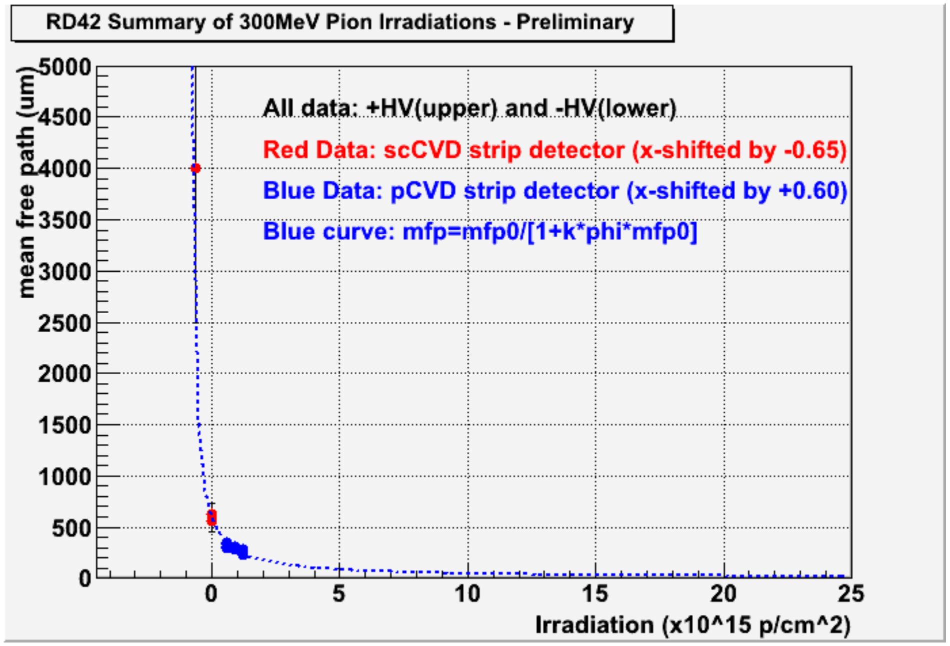
DPA Scaling seems better.
Predicts $k_{300\mathrm{MeV}\pi} = k_{70\mathrm{MeV}p} \approx 2.6\times$ 24GeV p

Pion Irradiation - PSI 200 MeV pions:

Damage equation:

$$\frac{1}{\mathrm{mfp}} = \frac{1}{\mathrm{mfp}_0} + k\phi$$

- mfp_0 initial traps in material
- k damage constant
- ϕ fluence
- Assume $\mathrm{mfp}_e = \mathrm{mfp}_h$



New results from pion irradiation

Test beam data shown - source overestimates damage

Same damage curve: 1/mfp=1/mfp$_0$ +k ϕ $\rightarrow k = 1.8 \times 10^{-18} \mu m^{-1} cm^2$

200 MeV pions 2.5-3.0$\times$ more damaging than 24 GeV proton

Summary of Proton and Pion Irradiations:

Particle	Energy	Relative k
p	24GeV	1.0
	800MeV	1.6-1.8
	70MeV	2.5-2.8
	25MeV	4.0-5.0
π	200MeV	2.5-3.0

Damage curves are beginning to be mapped out

Applications

Applications

CVD Diamond Used or Planned for Use in Several Fields

- High Energy Physics
- Heavy Ion Beam Diagnostics
- Sychrotron Radiation Monitoring
- Neutron and α Detection
- Dosimetry (radiation treatment, space)

Applications Discussed Here

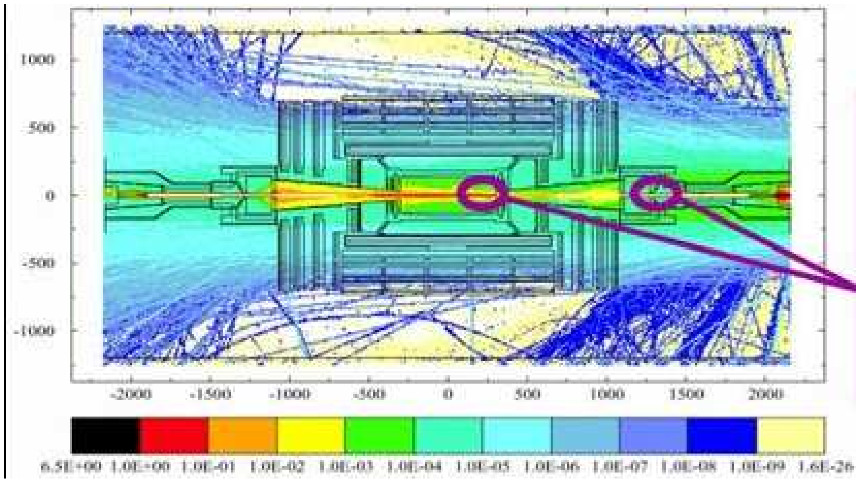
- Beam Conditions Monitoring
  - BaBar, Belle, CDF
  - ATLAS, CMS, LHCb, Alice
- Pixel Detectors - innermost layer
  - ATLAS, CMS

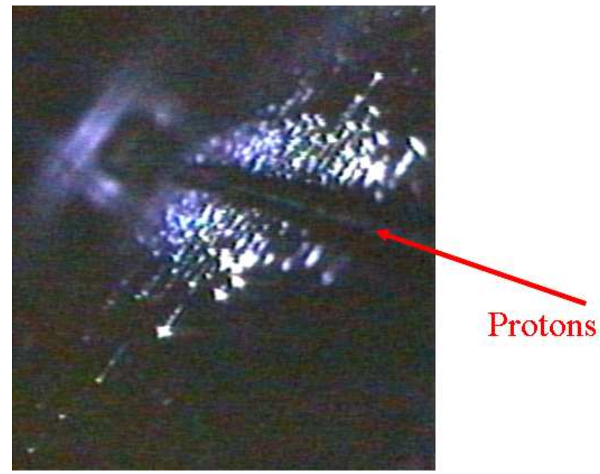
Beam Condition Monitoring

- current measurement
- single particle counting
- monitoring, protection

Motivation:

- → Radiation monitoring crucial for Si operation/abort system
- → Abort beams on large current spikes
- → Measure calibrated daily and integrated dose





Style:

- DC current or Slow Readout
- Requires low leakage current
- Requires small erratic dark currents
- Allows simple measuring scheme

- Examples: BaBar, CDF, ATLAS, CMS

- Single Particle Counting
- Requires fast readout (GHz range)
- Requires low noise
- Allows timing correlations

- Example: ATLAS, CMS

Beam Conditions Monitoring - BaBar

M. Bruinsma, P. Burchat, S. Curry, A. Edwards, H. Kagan, R. Kass,
D. Kirkby, S. Majewski, B. Petersen

The BaBar Diamond Radiation Monitors:

- $\rightarrow$ BaBar originally used silicon PIN diodes, leakage current increases 2nA/krad
- $\rightarrow$ After 100fb^{-1} signal$\approx$10nA, noise$\approx$ 1-2μA
- $\rightarrow$ Large effort to keep working, BaBar PIN diodes (H-plane) did not last past 2005

Photo of BaBar Prototype Devices

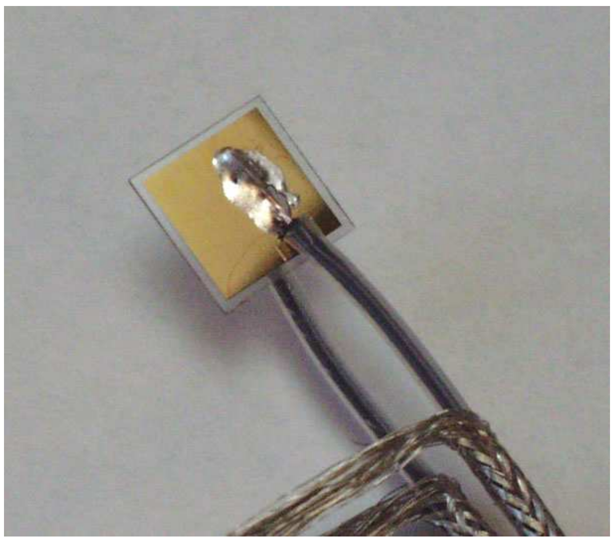
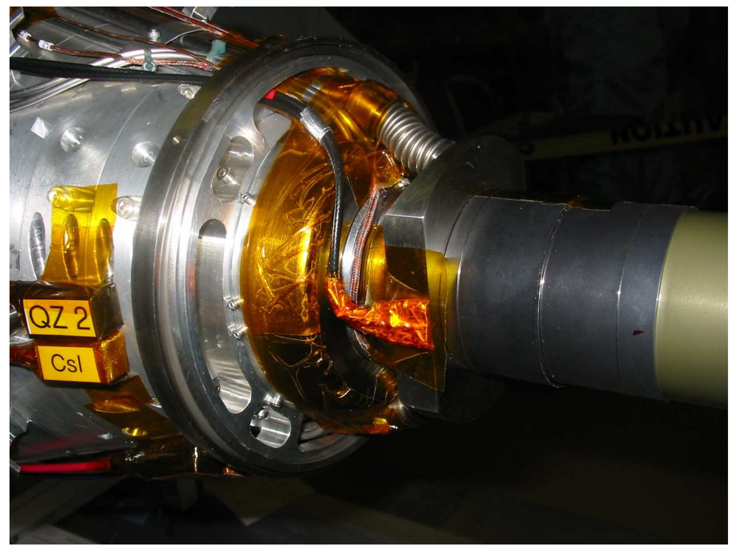
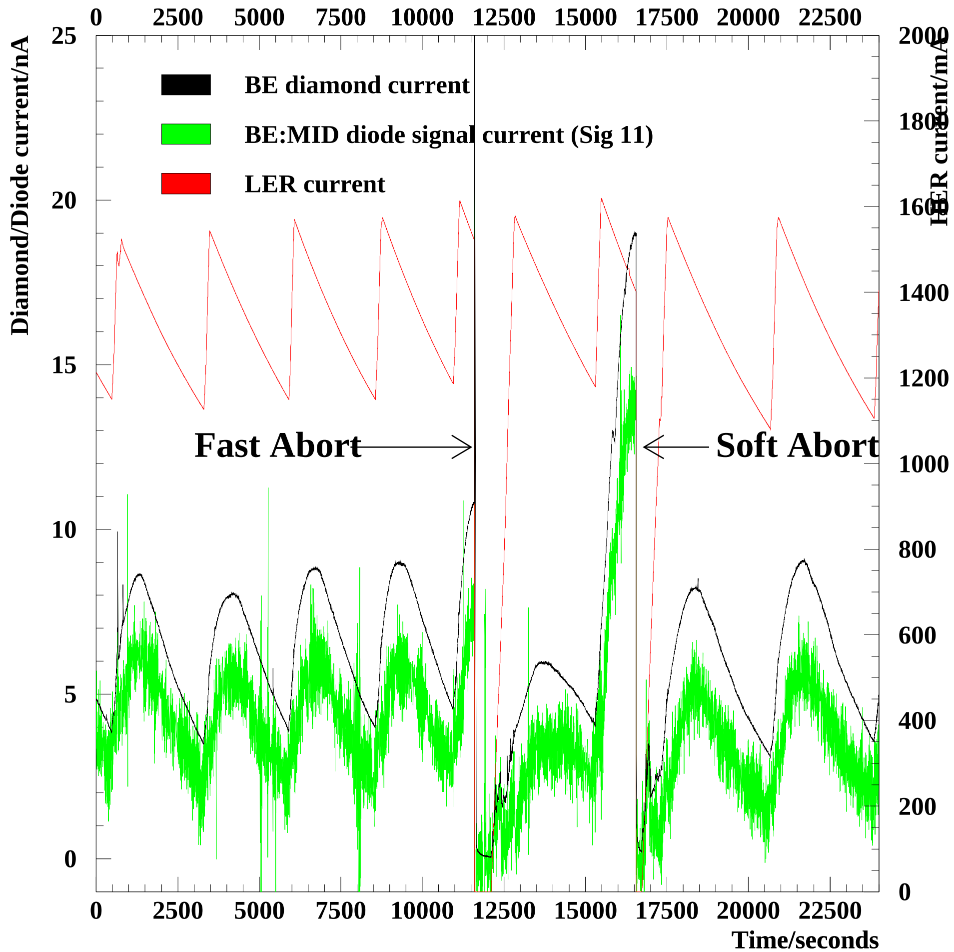


Photo of Installed BaBar Device



Data Taking in BaBar:



- *System operated for >5 years in BaBar and worked well!*
- *Diamonds took over for PIN diodes in the horizontal plane.*

Beam Conditions Monitoring - CDF

P. Dong, R. Eusebi, A. Sfyrla, R. Tesarek, W. Trischuk, R. Wallny

The CDF Diamond Radiation Monitors:

Photo of CDF Prototype Devices

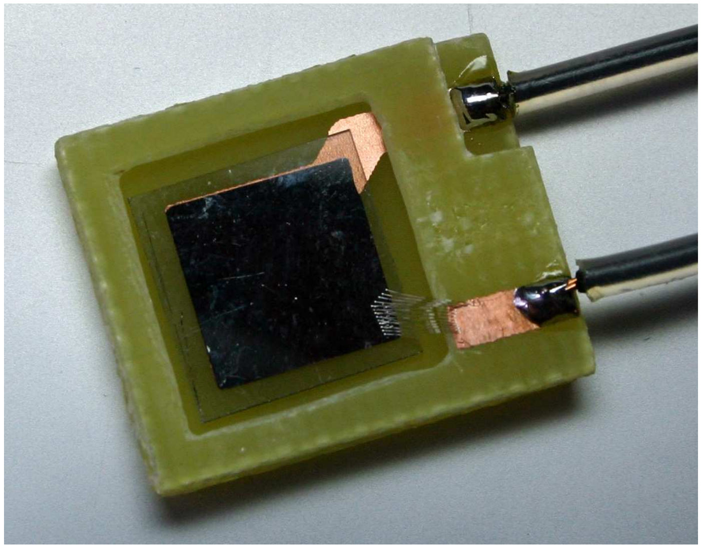
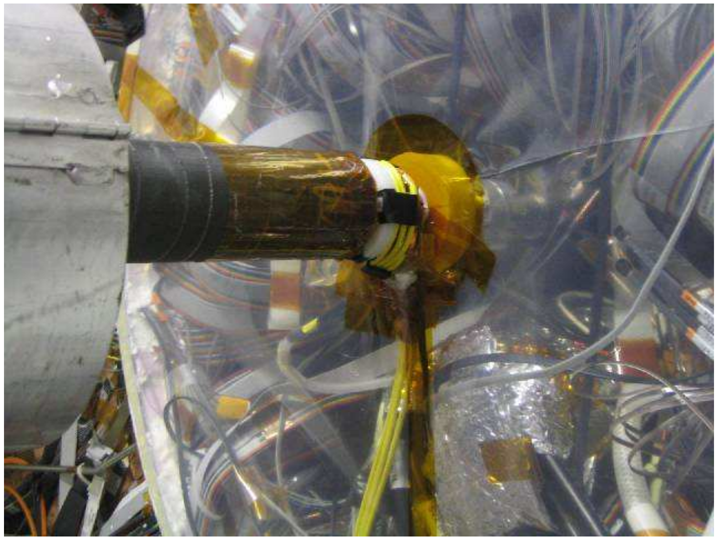
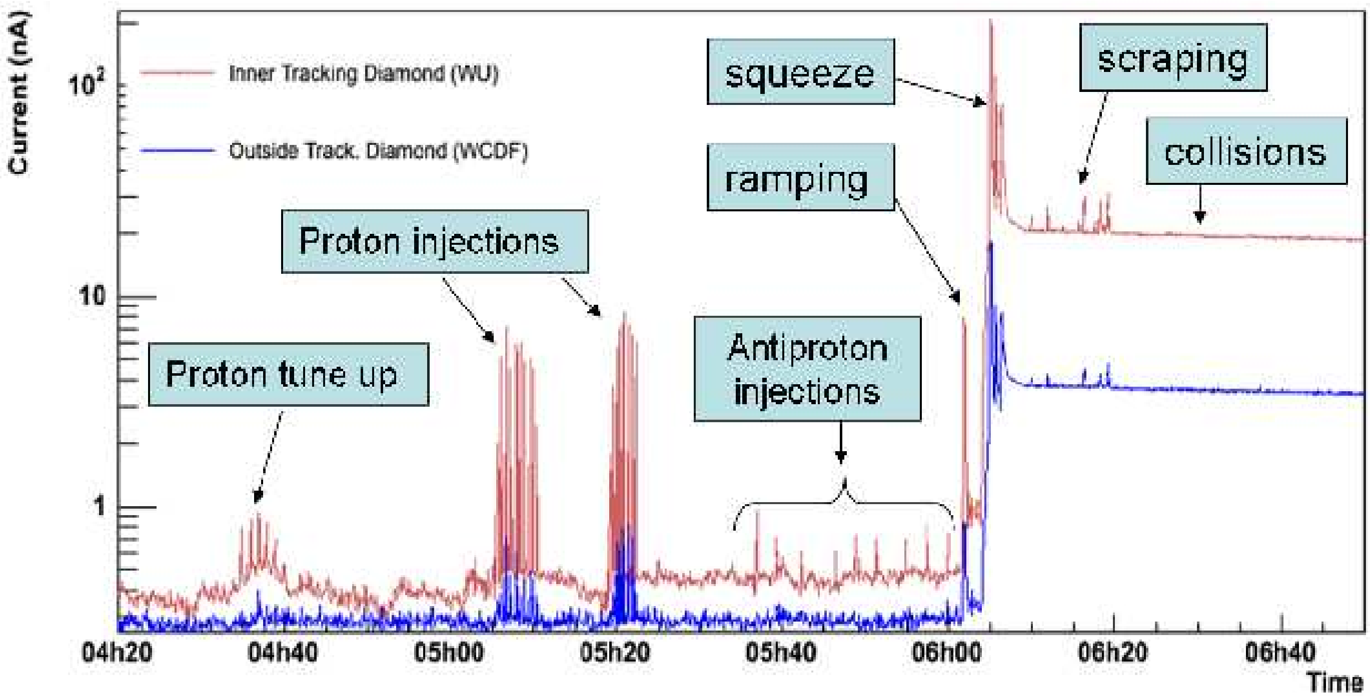


Photo of Installed CDF Device



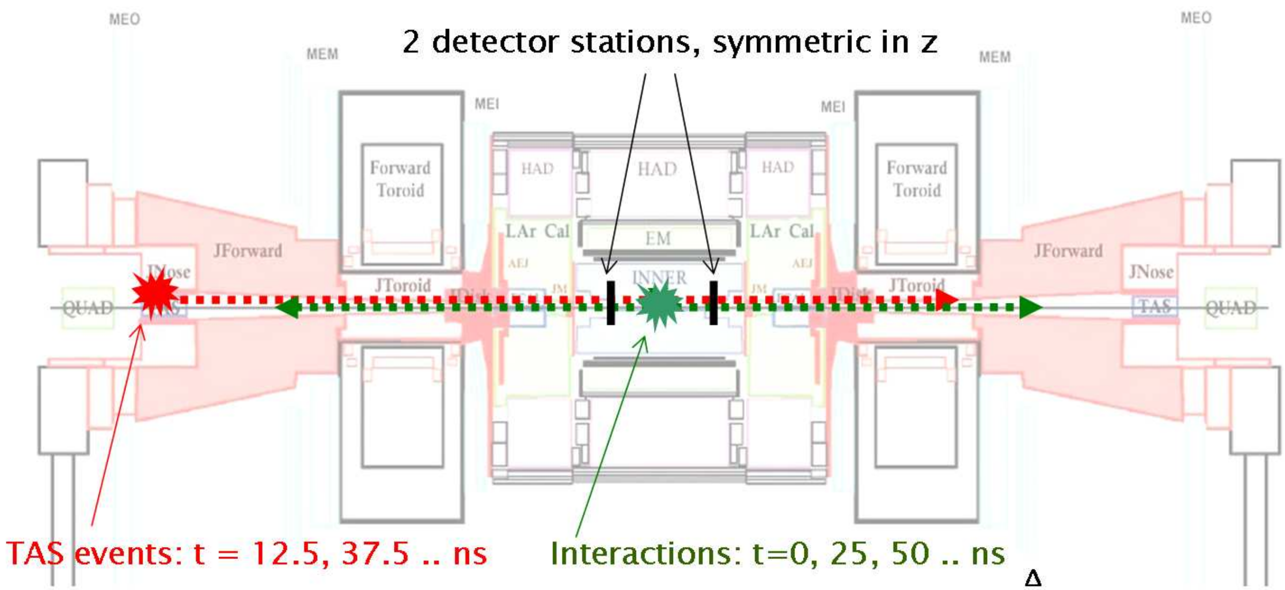
- The installed CDF device has thirteen diamonds
- Eight inside CDF - four per side
- Five outside the experiment at calibration stations near Beam Loss Monitors (BLM's)

Data Taking in CDF:



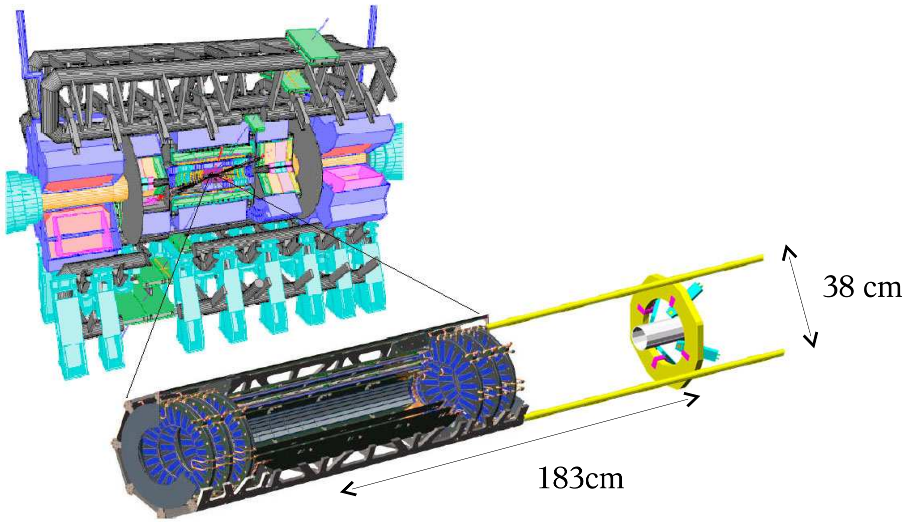
- *Two diamonds operating in CDF since Fall 2004.*
- *Full system installed - June 2006!*
- *Inside detector is the place to be by an order of magnitude!*

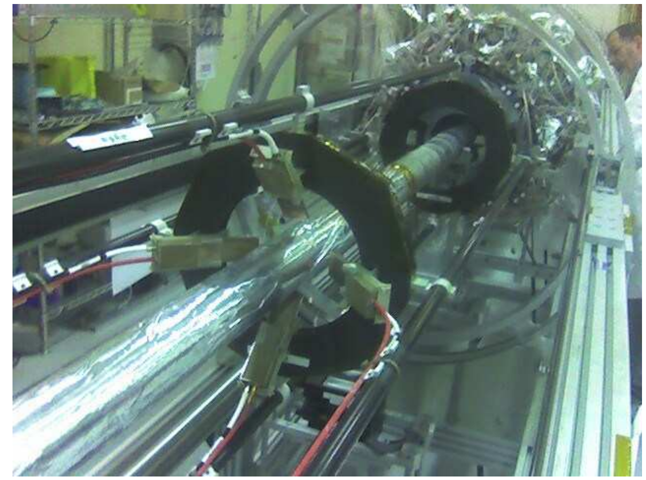
Idea: Time of flight measurement to distinguish collisions from background

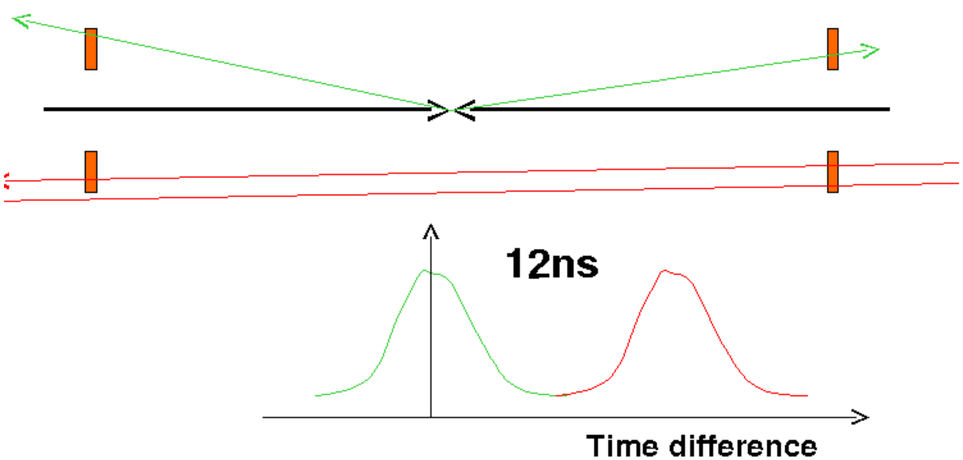


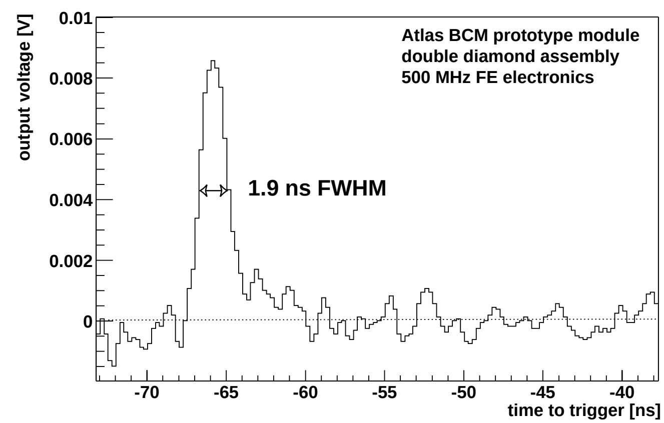
- For high luminosity need segmentation either in spatially or in time $\rightarrow$ time segmentation
- Detectors placed at $z = \pm$ 1.9m and $r =$ 55mm ($\eta \sim 4.2$, Δt $= 12.3$ns)
- Detectors must be able to withstand ~50Mrad in 10yrs
- Detectors plus electronics must have excellent time resolution (~1ns rise time, 2-3ns pulse width, 10ns baseline restoration)

Design: Inside the ATLAS Beam Pipe Support Structure (BPSS)



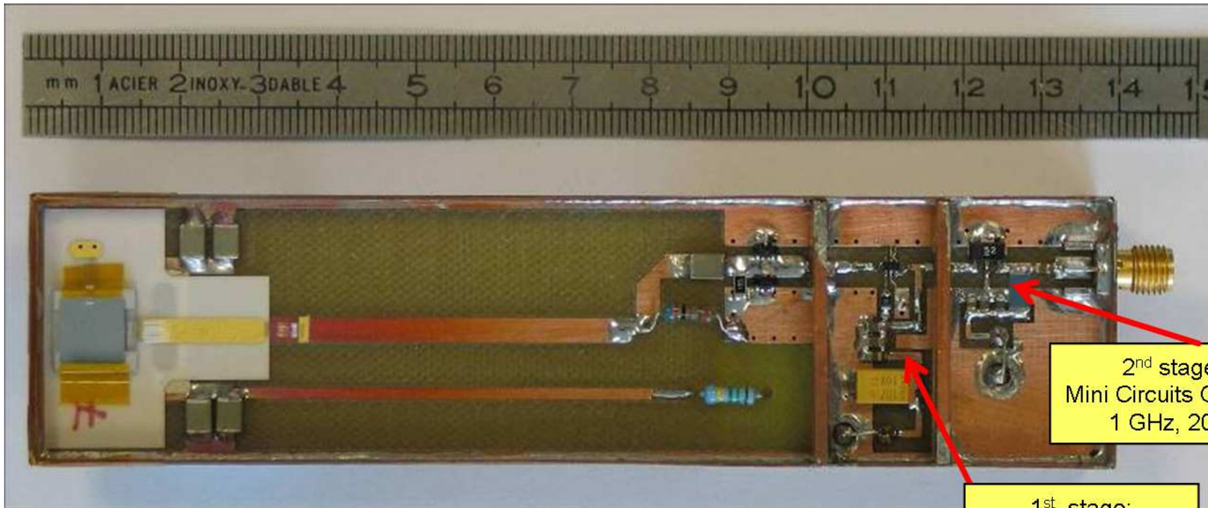


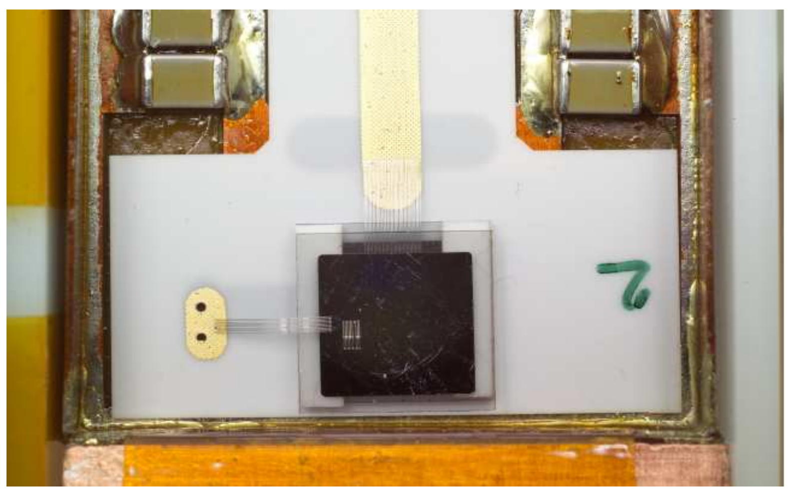




ATLAS BCM - Mechanics

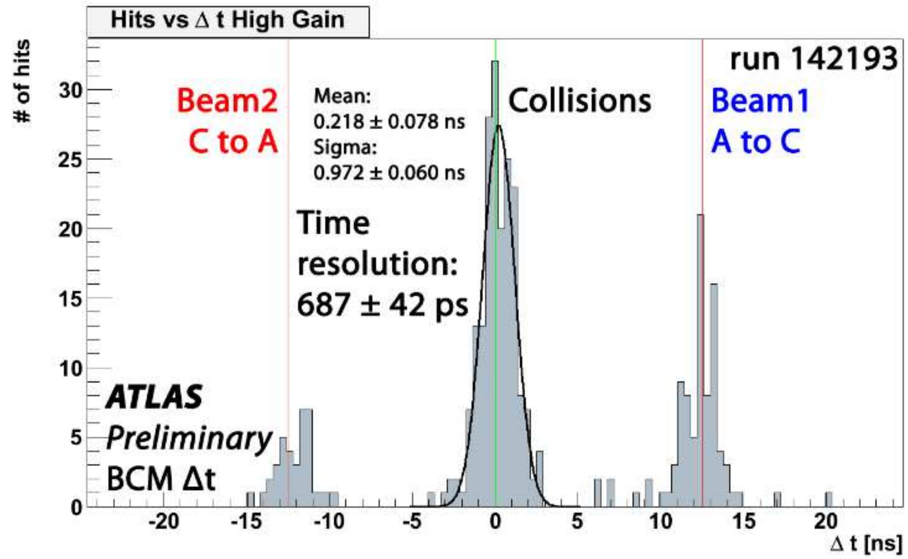
Mechanical Assembly:



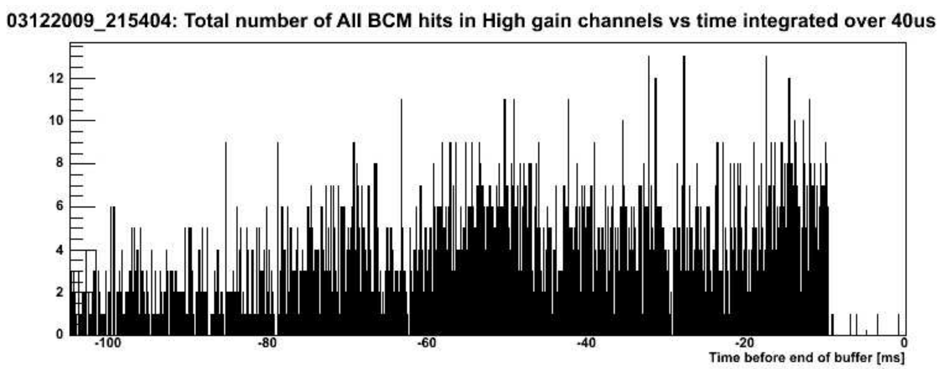


Present Status

Timing in LHC Data:



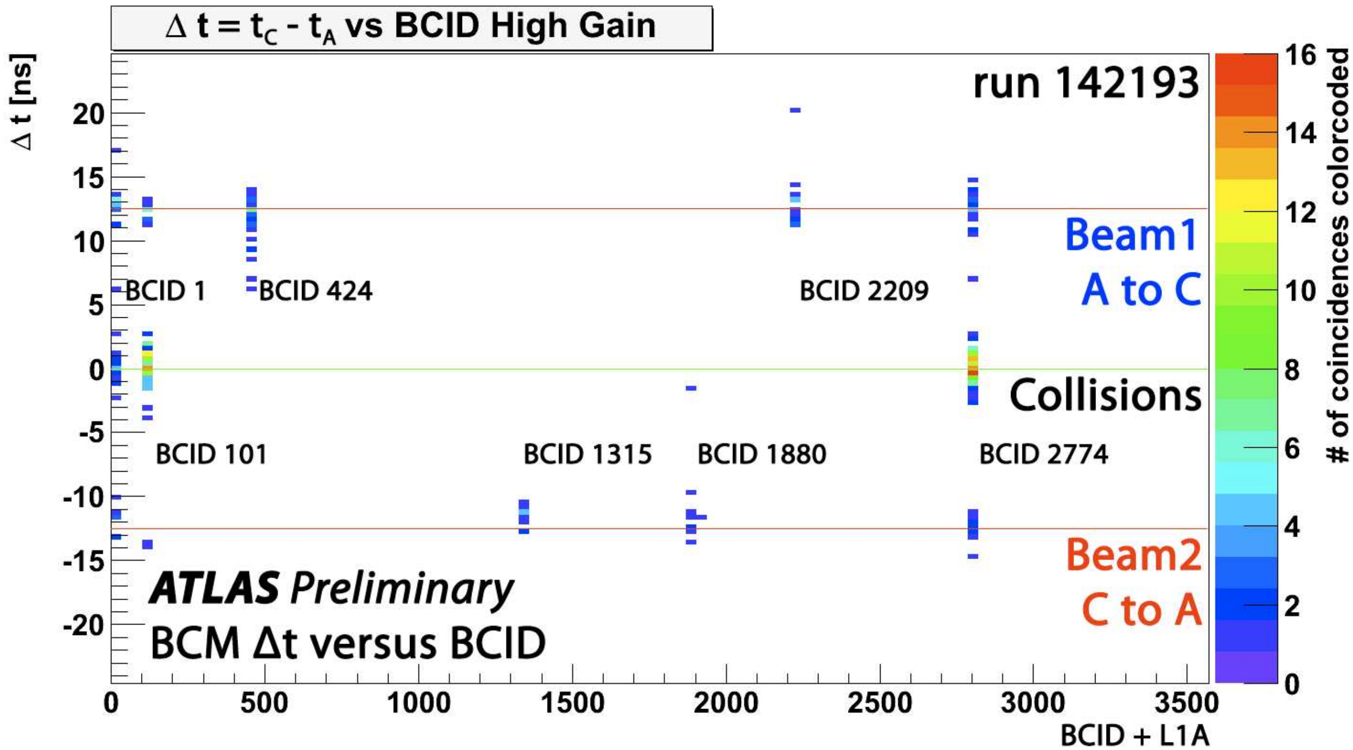
Abort in LHC Data:



BCM stores a record of 1177 +100 orbits for Post Mortum of an abort.

Present Status

BCM in LHC Data:



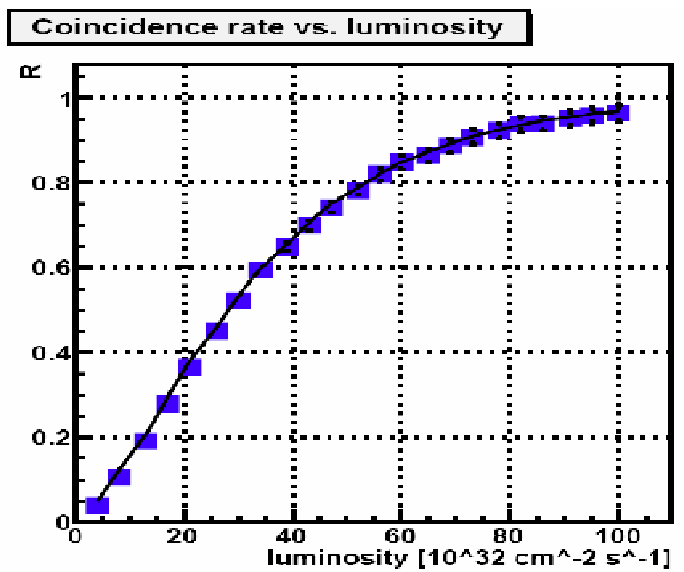
Can also tell which bunches give the most background!

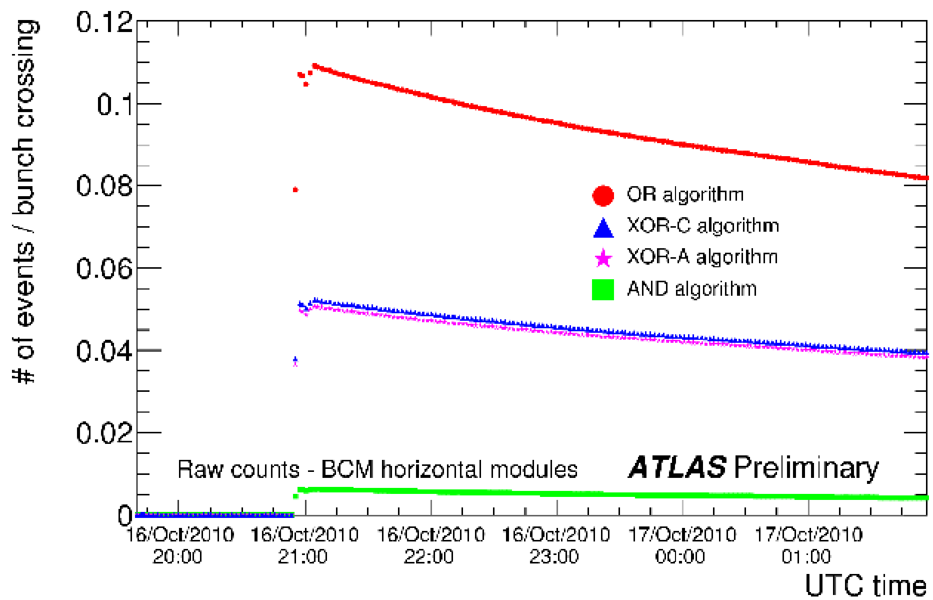
The BCM device is installed in ATLAS and taking data!

Present Status

BCM in LHC Data:

- Luminosity measurement at high rate is a difficult problem which can only be solved with segmentation - in space or time
- The ATLAS BCM solves this problem with time segmentation and a variety of algorithms (OR, XOR, AND)
- Even with the excellent time segmentation the ATLAS BCM will begin to saturate at 10^{34}



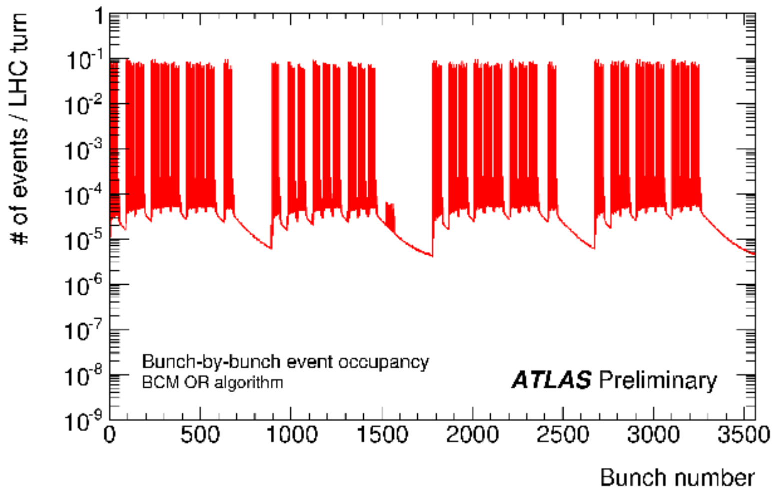


The BCM device presently provides the ATLAS Luminosity measurement

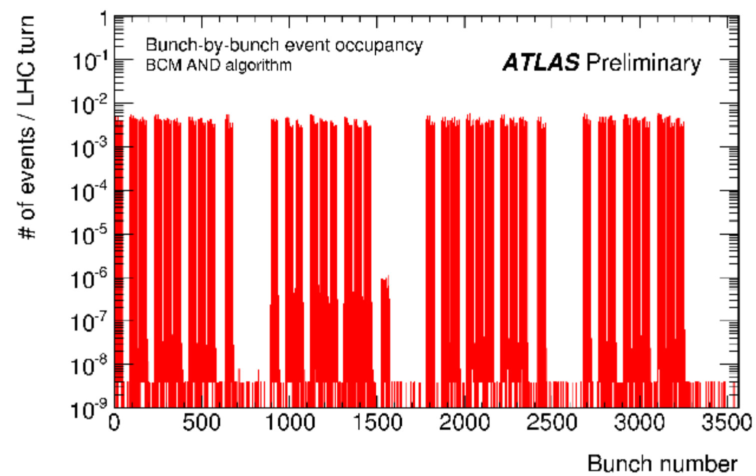
BCM in LHC Data:

- With good enough time resolution a device can measure individual bunch luminosity
- The BCM has the time resolution (0.7ns) to measure signal (12ns coincidence) rates and measure background (out of time) rates
- Also see "afterglow"

BCM OR



BCM AND

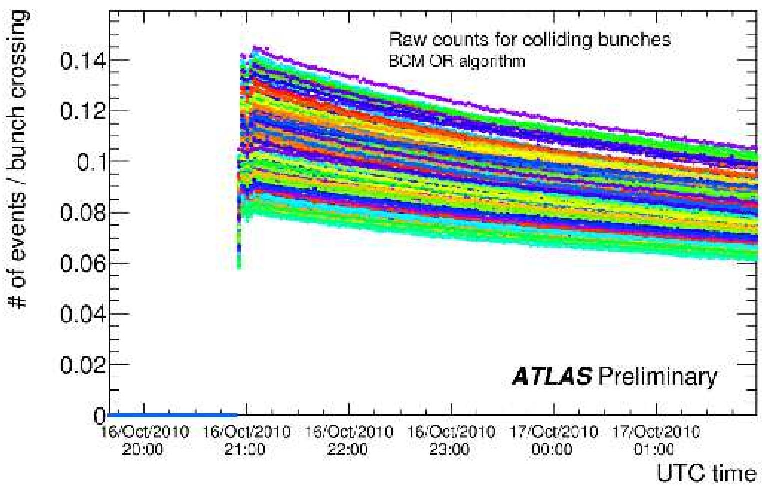


The BCM device provides the ATLAS with Bunch Counting

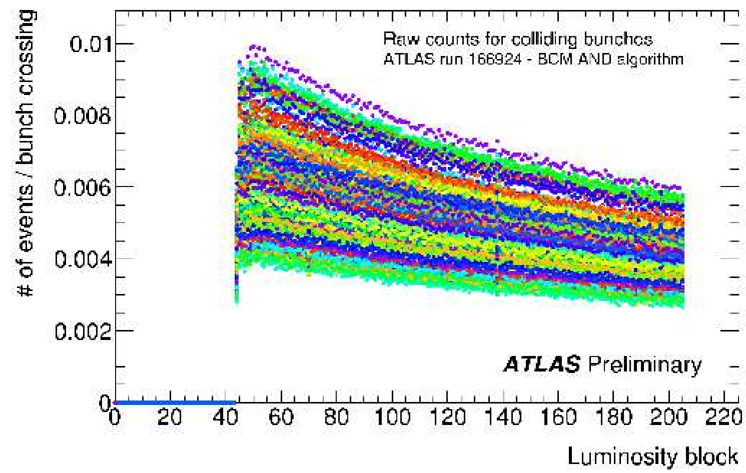
BCM in LHC Data:

- Using in-time and out-of-time rates → bunch-by-bunch luminosity

BCM OR



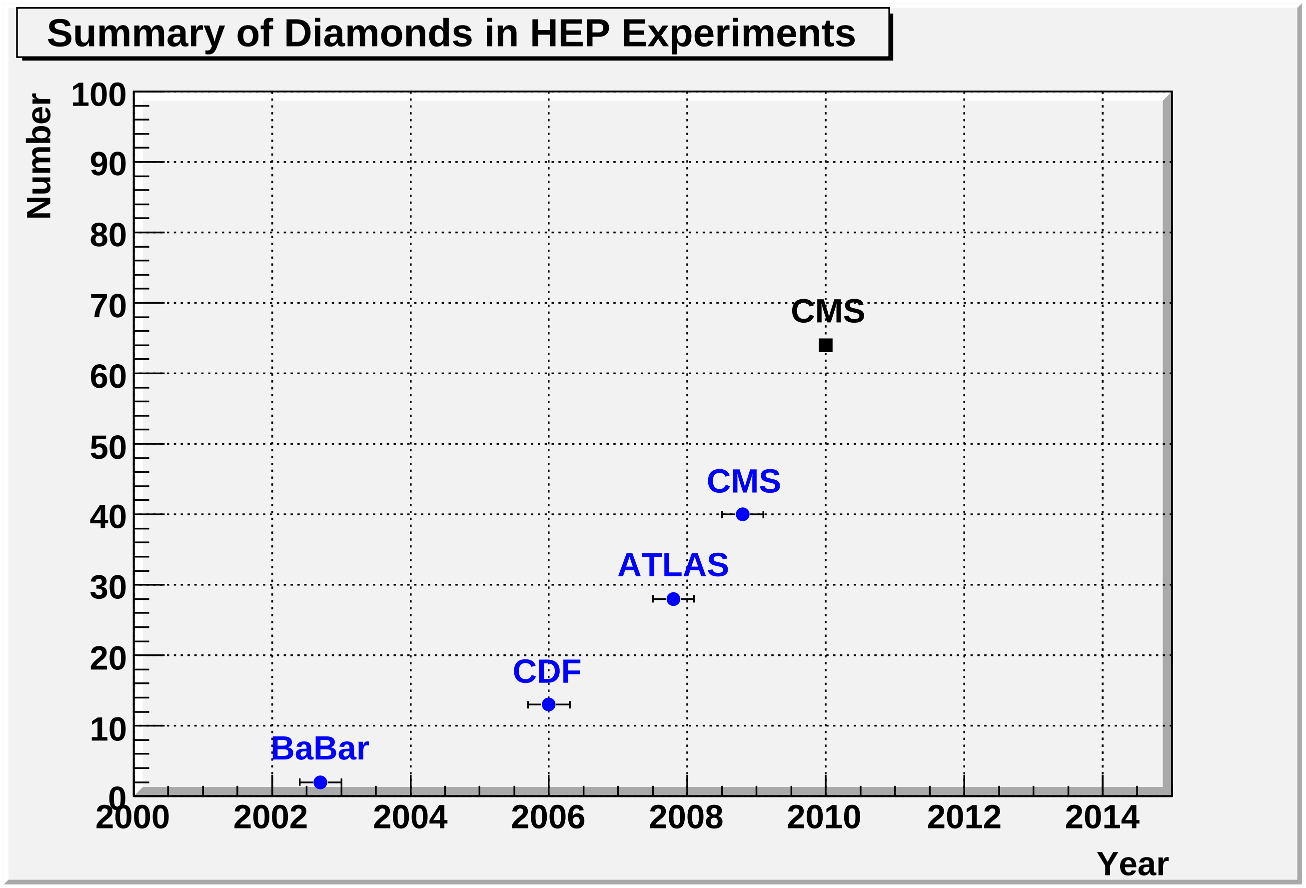
BCM AND



The BCM provides the ATLAS individual Bunch Luminosity

This leads to a 3% Overall Luminosity measurement!

CVD Diamond Used in High Energy Physics Experiments

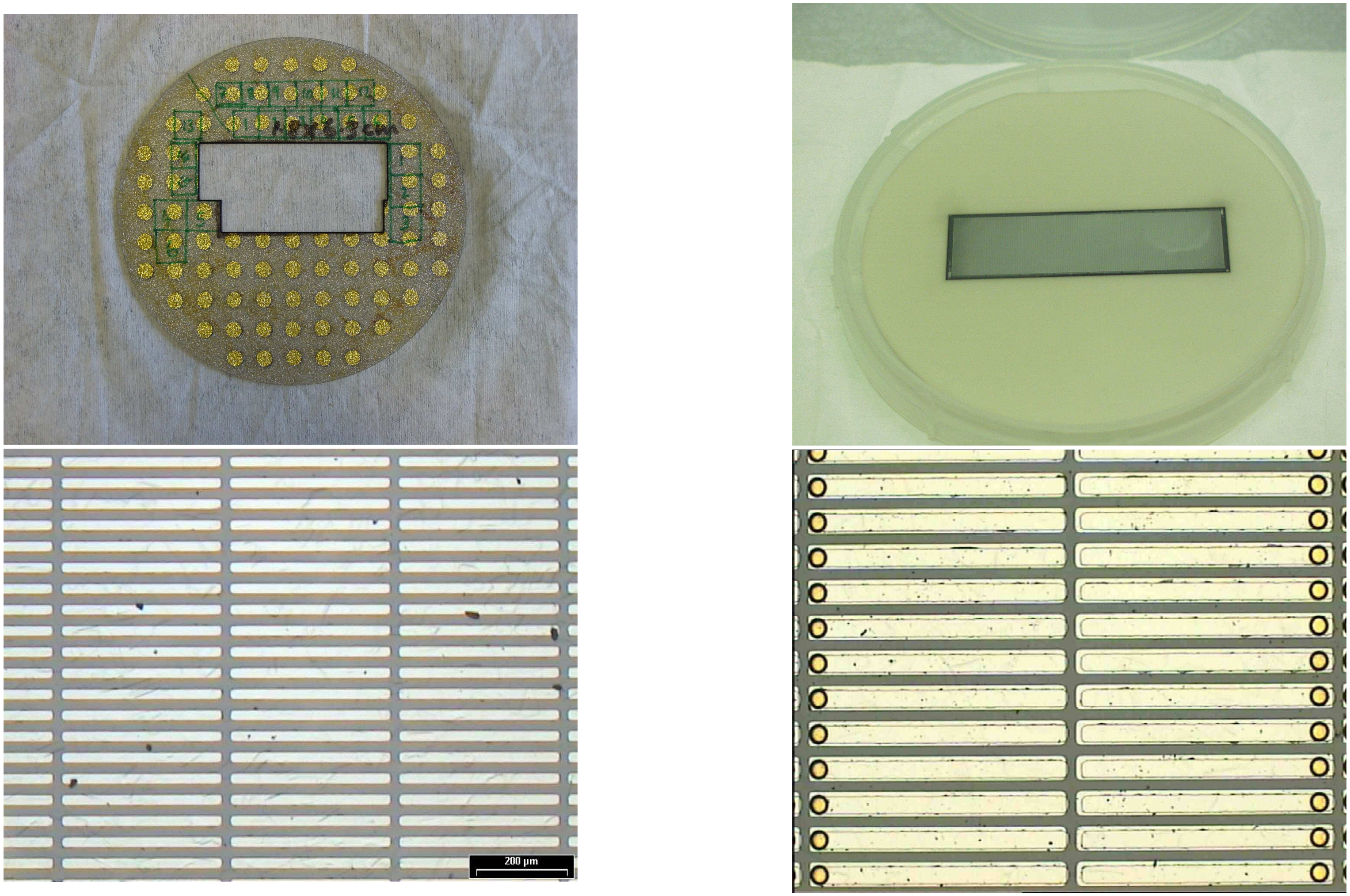


Blue data installed; black data under construction.
Diamond is becoming accepted.
Future?

pCVD and scCVD Pixel Detectors

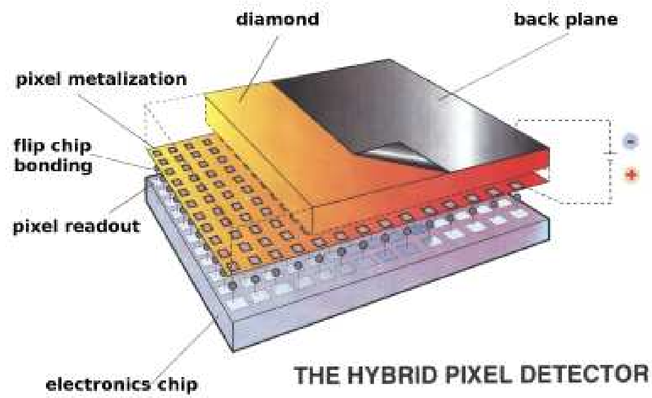
- signal
- noise, threshold, overdrive
- charge sharing, signal over threshold

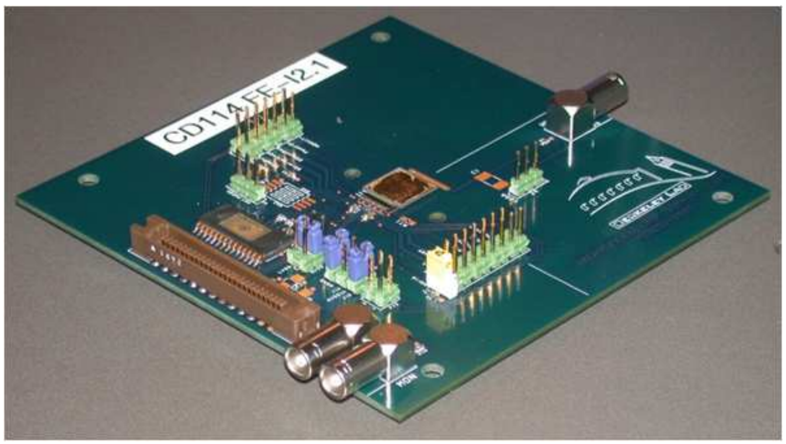
Constructing a full ATLAS Diamond Pixel Module:

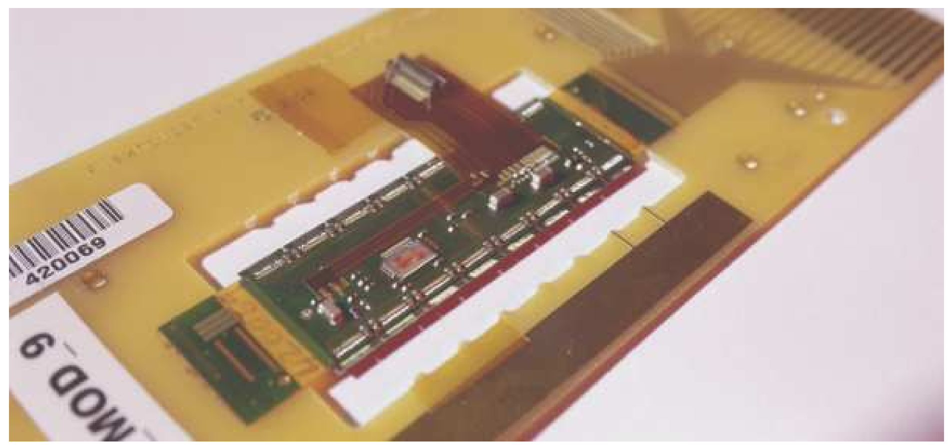


Various stages of making a module - growth, metalization, carrier support, bump-bonding, electronics, testing.

Full 16 Chip and 1 chip ATLAS diamond pixel modules

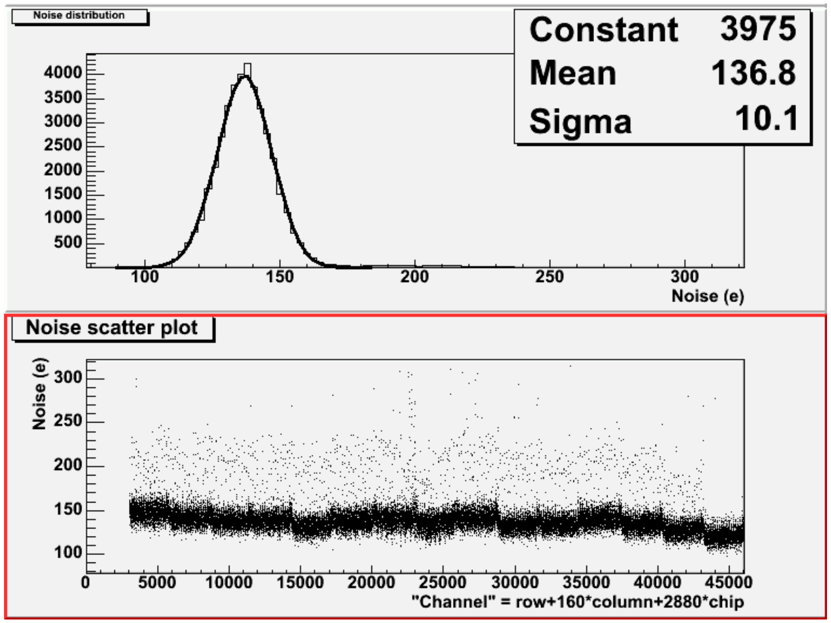


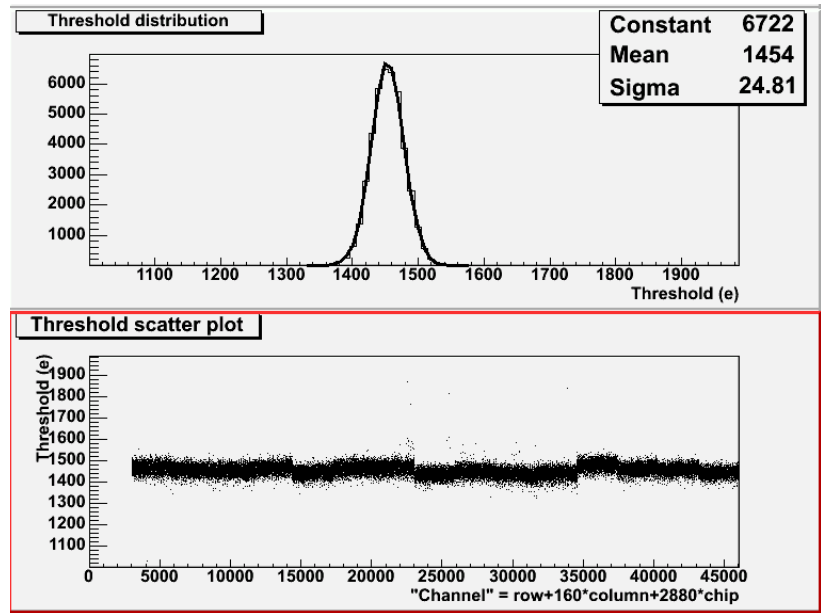




- Single chip and full modules bump-bonded at IZM (Berlin), constructed and tested in Bonn
- Operating parameters (FE-I3): Peaking Time 22ns, Noise 140e,Threshold 1450-1550e, Threshold Spread 25e, Overdrive 800e

The full ATLAS diamond pixel module - Noise, Threshold



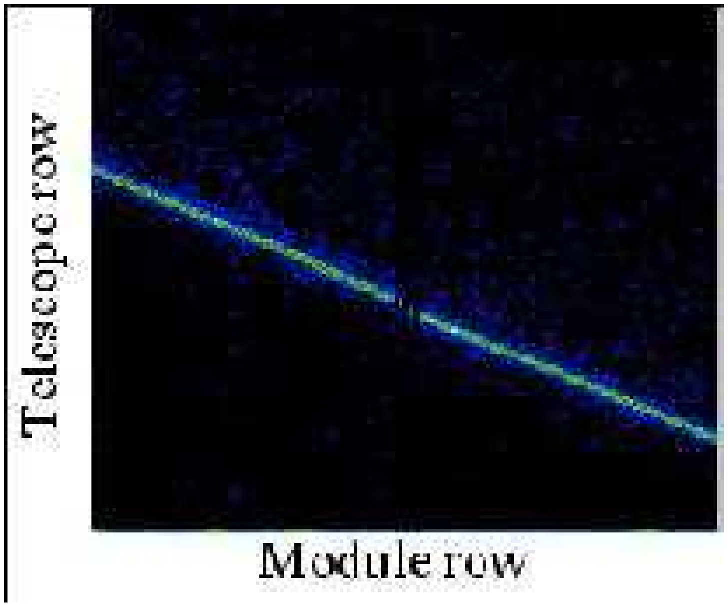


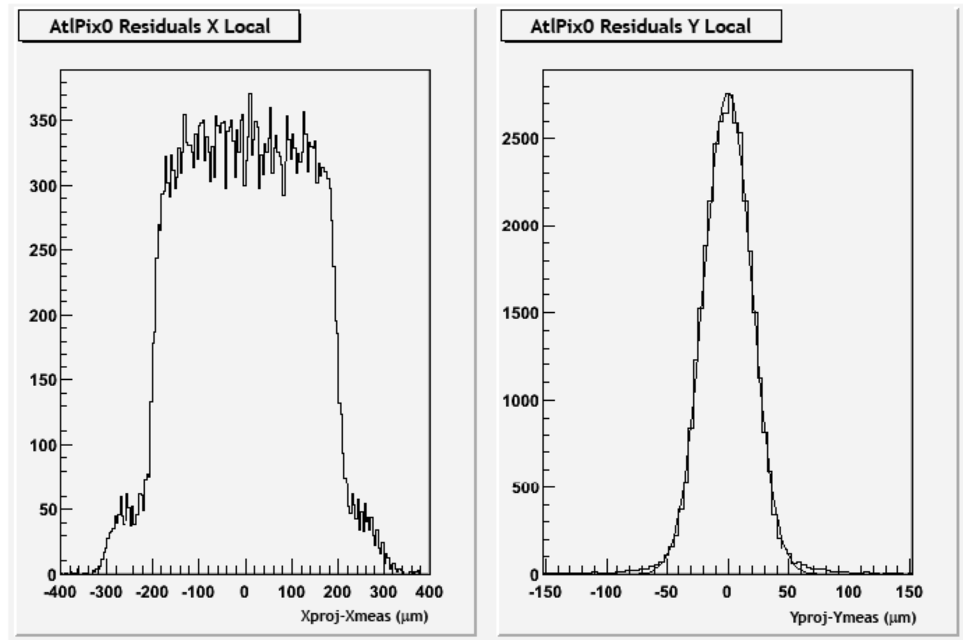
Results: Noise $\sim 137e$, Mean Threshold $1454e$, Threshold Spread $\sim 25e$.
Noise, threshold, threshold spread do not change from bare chip.

$\rightarrow$ Advantage of low capacitance, no leakage current

ATLAS Diamond Pixel Detectors

The full ATLAS diamond pixel module - Correlation, Resolution



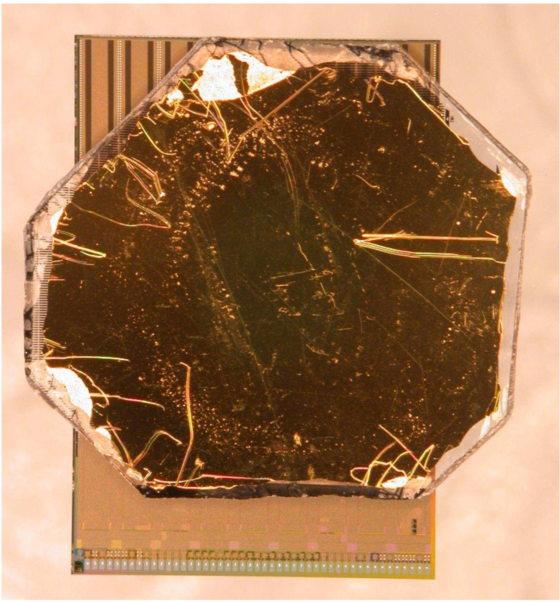


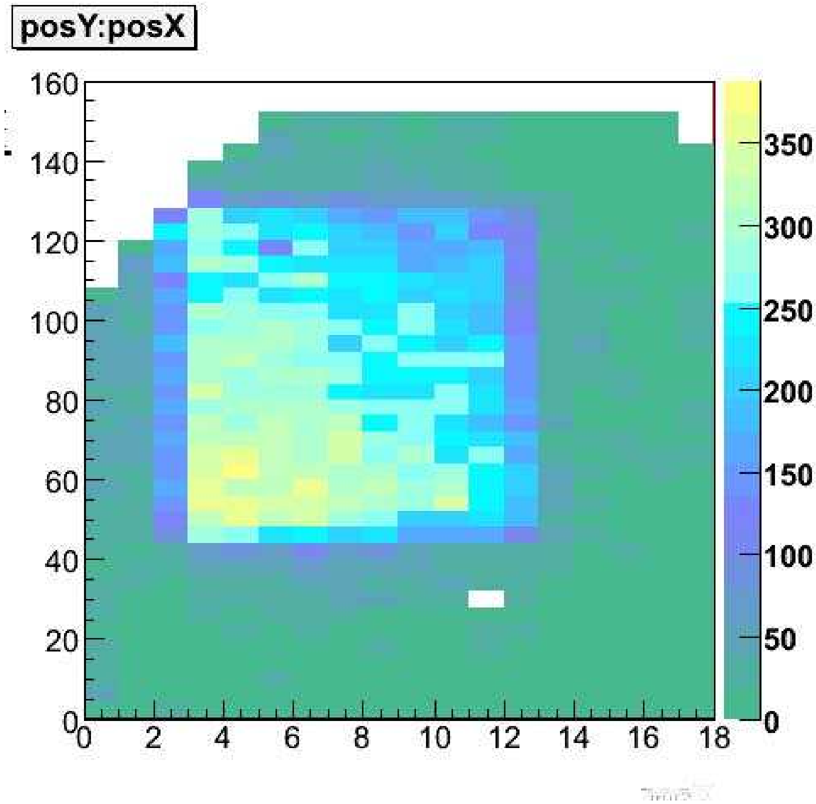
Excellent correlation with telescope

Resolution dominated by 6 GeV electron multiple scattering.

Residual $\sim 18\mu$m - remove telescope tracking contribution $\rightarrow 14\mu$m.

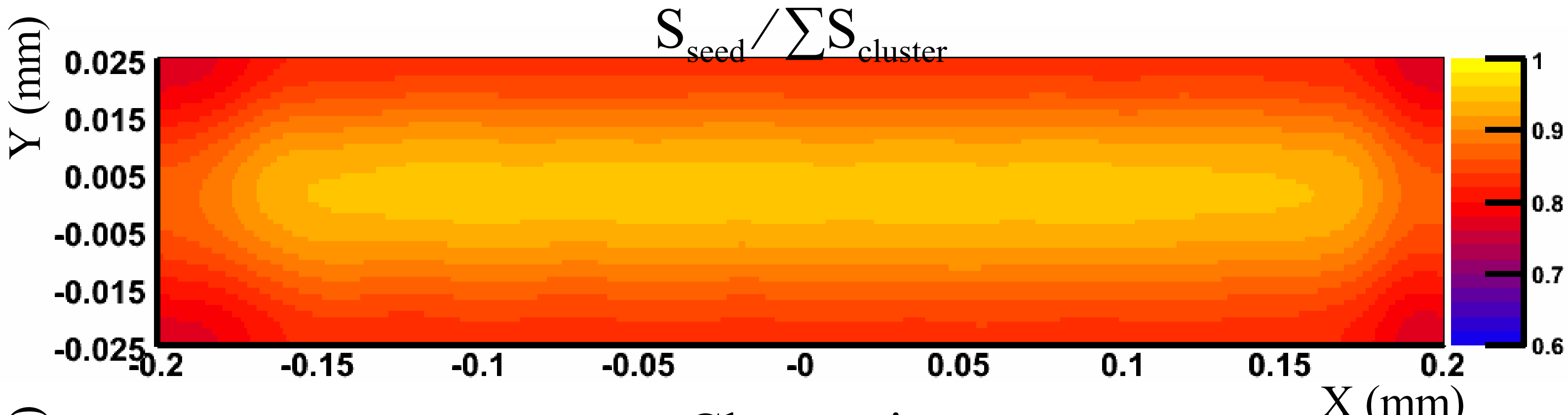
The First scCVD ATLAS diamond pixel detector

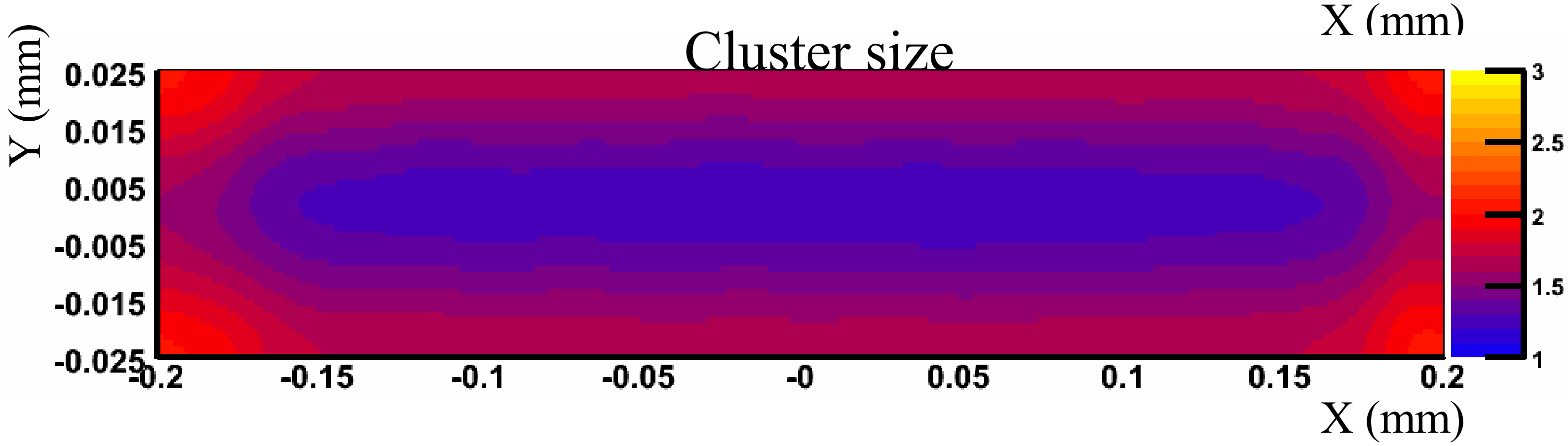




- The first device → odd shaped but looks good
- The hitmap plotted for all scintillation triggers with trigger in telescope.
- The raw hitmap looks goods - ∼ 1 dead pixel

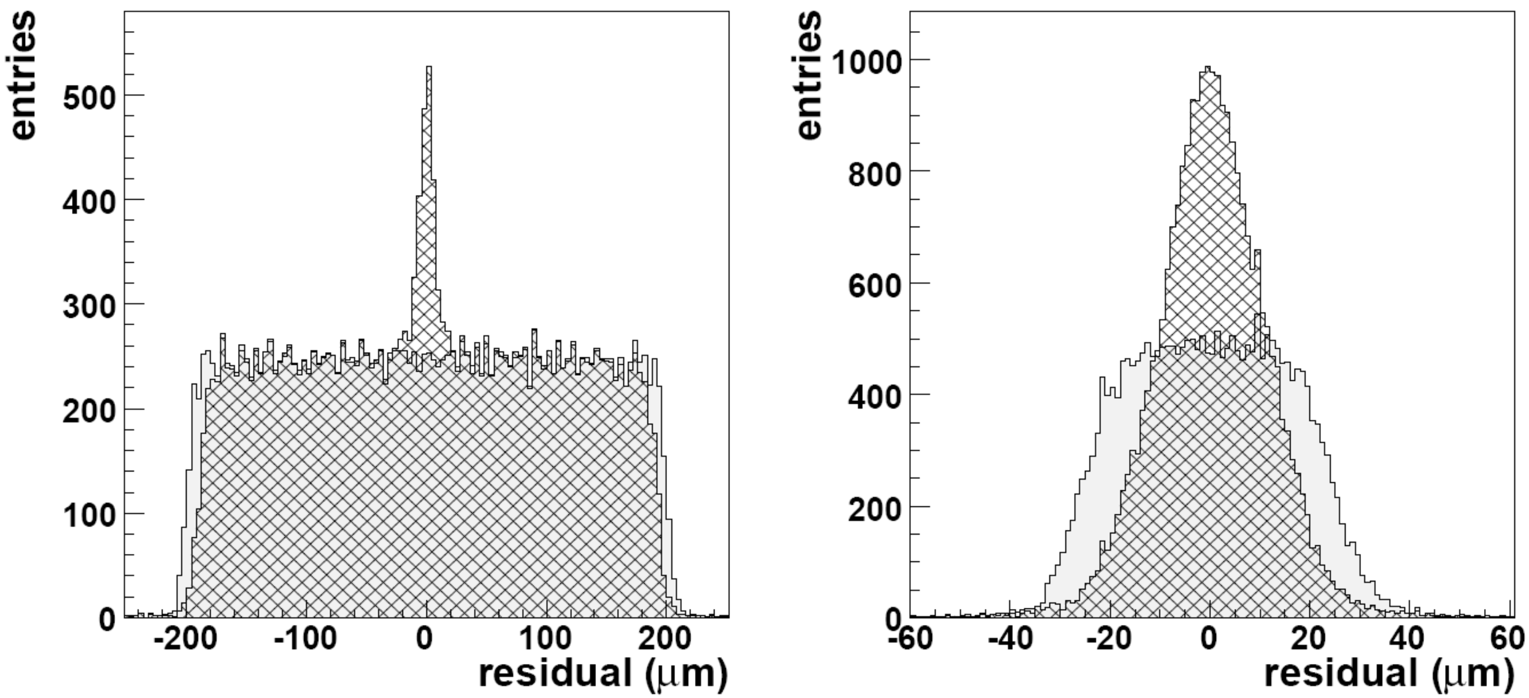
Last Year: The First scCVD ATLAS diamond pixel detector - Charge Sharing





- Map all events into 50μm $\times$ 400μm pixel cell
- Strips occupy Y-region $\pm$0.0125mm, X-region $\pm$0.175mm
- Charge sharing as expected!

Spatial Resolution (1-pixel and 2-pixel η)



- Plot contains all scintillator triggers with "track" trigger in telescope
- Diamond pixel resolution 8.9μm for normal incidence
- Signal/Threshold $\sim$ 8
- If geometry allows for charge sharing $\rightarrow$ lower threshold $\rightarrow$ more charge sharing observed $\rightarrow$ better spatial resolution.

Future Applications

Based on the successes of Diamond Beam Monitors and Diamond Pixel Detectors both ATLAS and CMS are proceeding to construct Diamond Pixel Telescopes for 1% Luminosity Measurement

ATLAS Diamond Beam Monitor:

- Diamond Type: pCVD
- Diamond Size: 18mm x 21mm
- Position from IP: 0.934m
- Active Length: 10cm
- Number of Devices: 24 = 4 Telescopes of 3 planes x 2 sides

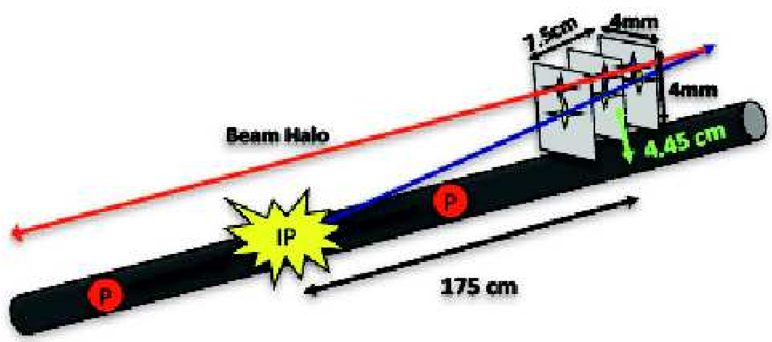
CMS Precision Luminosity Telescope:

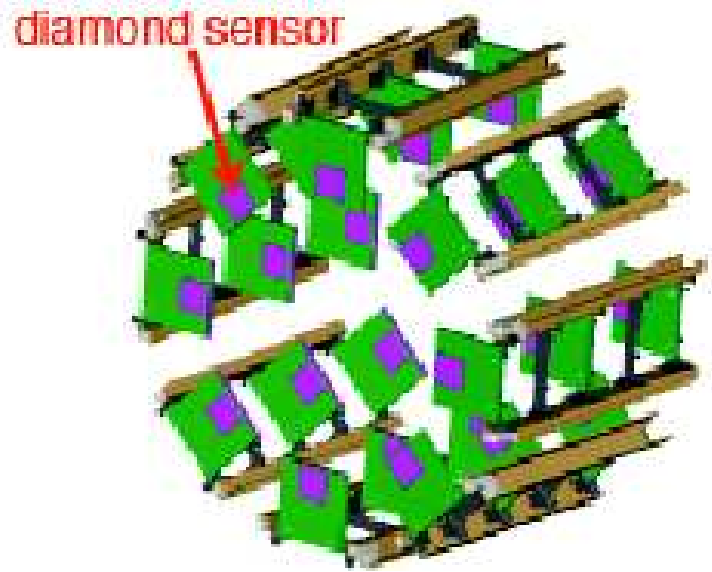
- Diamond Type: scCVD
- Diamond Size: 4mm x 4mm
- Position from IP: 1.75m
- Active Length: 7.5cm
- Number of Devices: 48 = 8 Telescopes of 3 planes x 2 sides

The ATLAS DBM and CMS PLT are comparable.

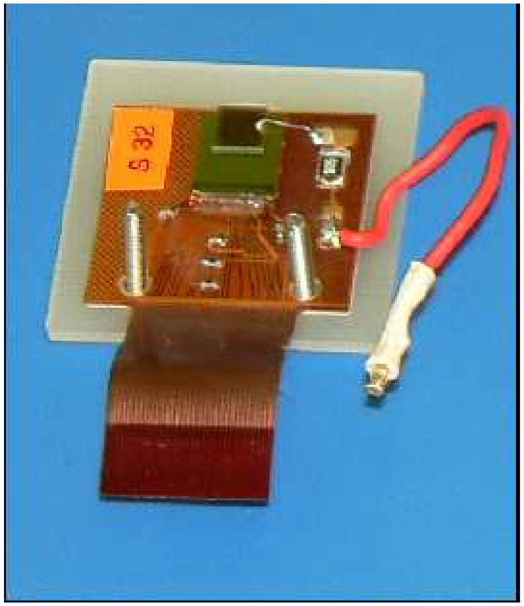
Future Applications

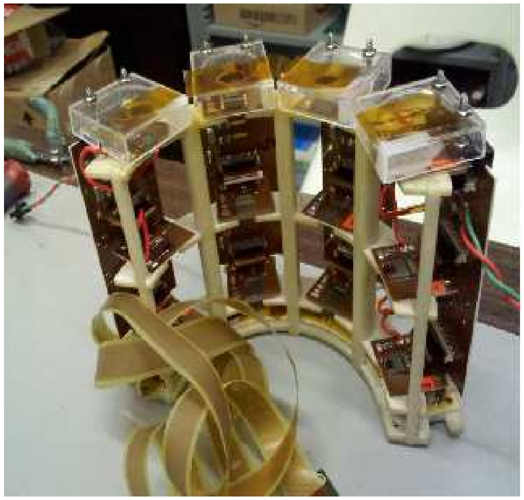
CMS PLT

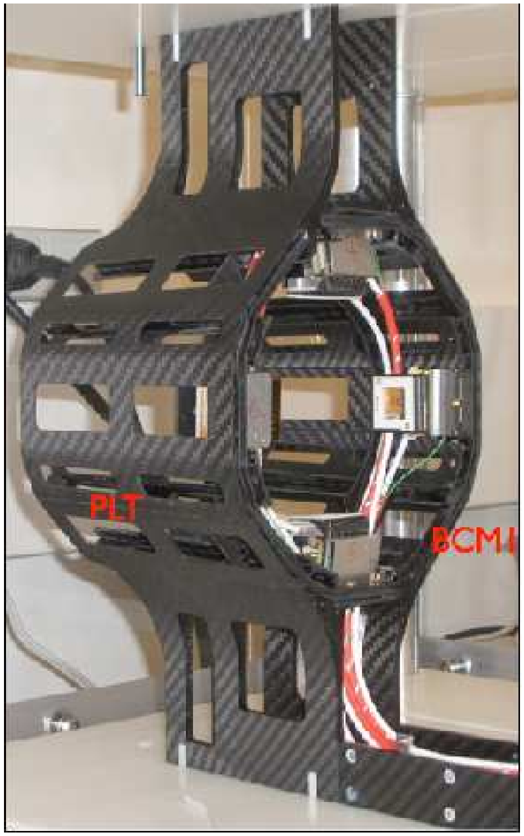




CMS PLT Photos

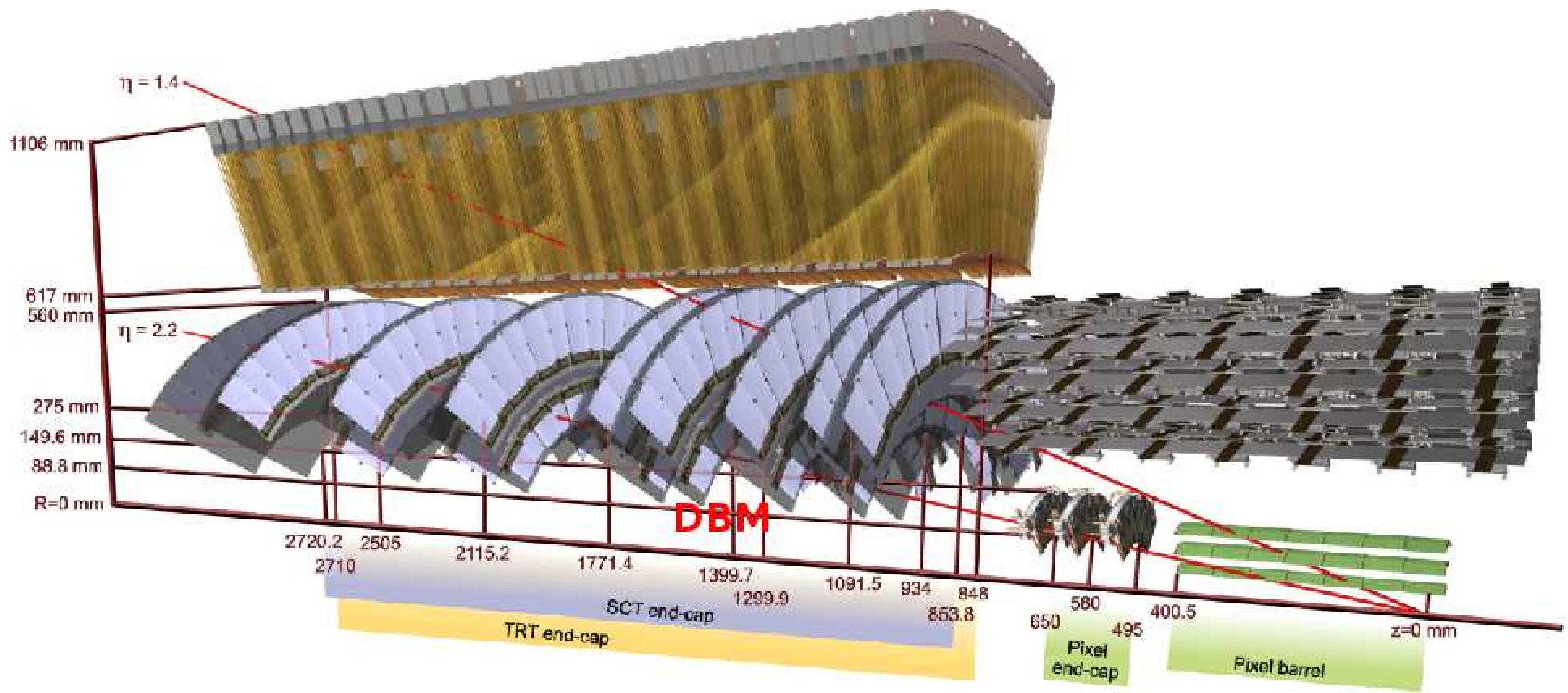




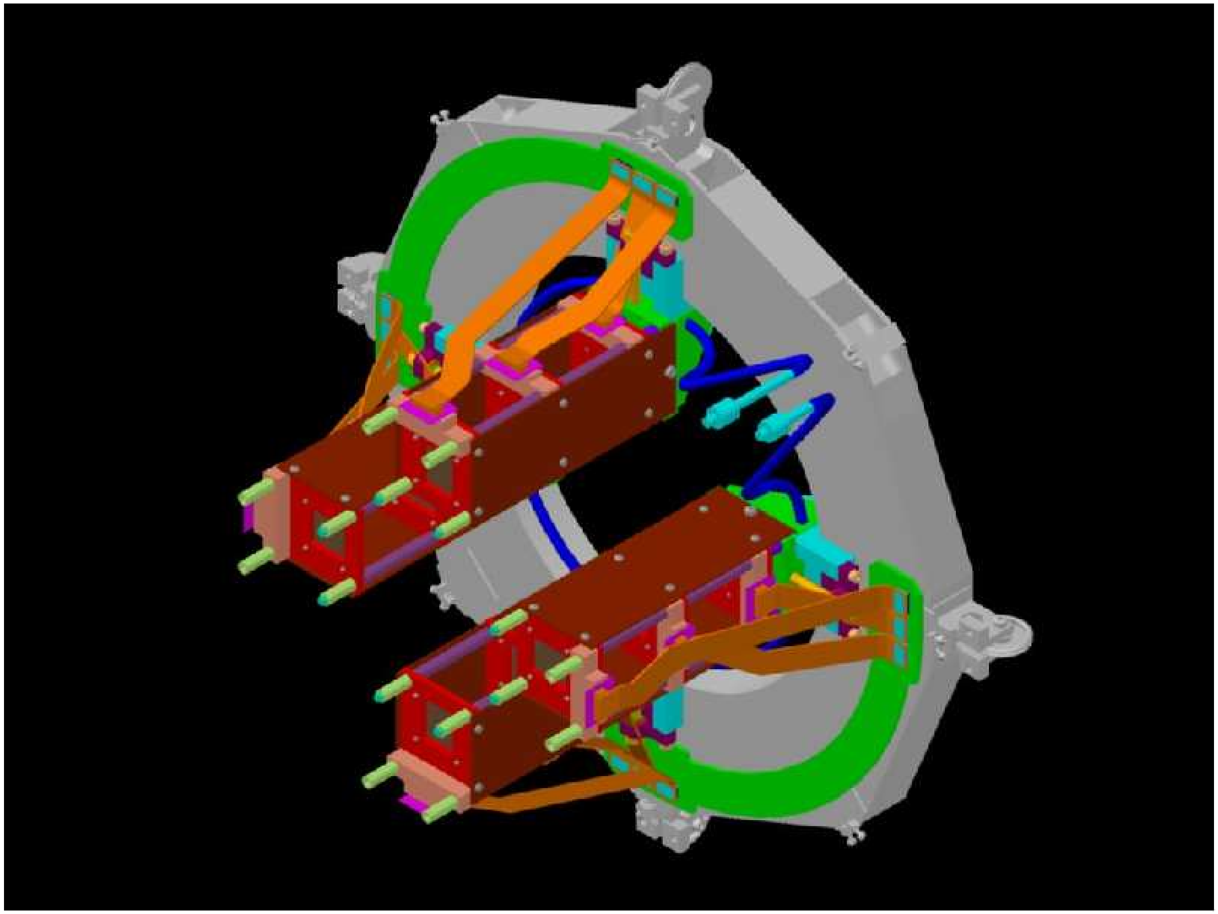


Future Applications

ATLAS DBM



ATLAS DBM



Summary

- **CVD diamond can be used for high energy radiation and particle detection**
  - Beam Conditions Monitors in BaBar, CDF, ATLAS, CMS LHCb, ALICE
  - Diamond Pixel Detectors being considered by ATLAS, CMS, LHCb
  - Diamond is competing with silicon technology in these areas
- **Radiation Hardness of CVD diamond is nearly quantified**
  - pCVD and scCVD have same damage curve
  - Damage curves for many energies and species
  - Dark current decreases with fluence
- **pCVD and scCVD electronic grade material is available.... but**
  - Still need to measure the quality of each sample
  - Surface properties are critical for good material
  - Would like pCVD with larger ccd; larger scCVD
- **New applications are developing as the material gets used!**